MACHINE CASTING OF FERROUS ALLOYS

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H. R. LARSON, B. A. HEYER and C. P. BISWAS
Abex Corporation
Research Center
Mahwah, N. J. 07430

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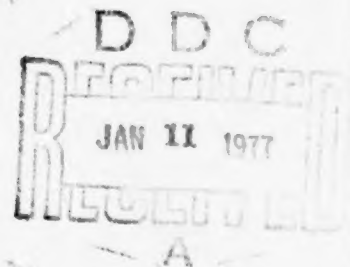
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An experimental ferrous casting machine of 20 lbs. capacity was designed and constructed to evaluate rheocasting and conventional casting processes. This machine is a bottom-pour furnace in which the transfer of the metal "slurry" to the mold was accomplished by pressurizing the furnace chamber and retracting a stopper rod. The melting and casting operation took place entirely under an inert atmosphere at low positive

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20. ABSTRACT (continued)

pressure to minimize slag formation. Several problems were encountered during the operation of the furnace and, therefore, the machine was redesigned and modified for more successful operation.

Several experimental models of both conduction and induction type MHD valves were made and it has been demonstrated that some lift can be obtained from these MHD devices to hold the bulk metal and to control its flow but a much stronger lift force would be required for any practical casting machine. Also some improvements have to be made to accomplish surface stabilization of the liquid.

Among all the protective coatings for graphite studied in this work, the most promising approach has been the formation of diffusion bonded metallic carbide on the graphite surface with plasma sprayed zirconia layer as the final mold surface. Hot pressed boron nitride and also silicon nitride have performed fairly well as permanent mold materials.

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FOREWORD

This report covers the complete work done during the contract period February 1, 1973 to September 30, 1975 under the general title "Machine Casting of Ferrous Alloys". The work was carried out at the Abex Research Center, Valley Road, Mahwah, New Jersey 07430 by the principal investigations, H.R. Larson, B.A. Heyer, and C.P. Biswas. The work was sponsored by the Defense Advanced Research Projects Agency under ARPA Order No. 2267 amd Contract No. DAAG46-73-C-0113 with Dr. E. Wright and Mr. F. Quigley at the Army Materials and Mechanics Research Center as the program technical monitor.

SUMMARY

An experimental ferrous casting machine of 20 lbs.
capacity was designed and constructed to evaluate rheocast-
ing and conventional casting with respect to processing and
properties. This machine consists of a bottom pouring in-
duction furnace in which the transfer of the semi-solid
metal to the mold was accomplished by pressurizing the chamber
and retracting a bottom pouring plug while the stirring
paddles were still on. The melting and casting operation
took place entirely under an inert atmosphere at low posi-
tive pressure to minimize slag formation. Several operational
difficulties were encountered during melting and pouring of
the melt such as freezing of the melt in the nozzle during
pouring, breakage of the stirring paddles and stopper rod,
heating of the pressure chamber cover, high resistance to
shaft rotation, etc. Therefore, the machine was redesigned
and modified for more successful operation. Although the
machine was ready for casting, it was decided to discontinue
any further work on this machine since our design did not
seem to be practical for production scale machine due to its
complications in construction and operation.

Several experimental models of both conduction and
induction type (and combinations thereof) MHD valves were

made (and proposed) and it has been demonstrated that some lift can be obtained from these MHD devices to hold the bulk metal and to control its flow but a significantly stronger levitation force would be required for any practical casting machine. Moreover, some improvements are necessary to accomplish stabilization of metal-air interface that causes the valve to leak.

For permanent mold application for ferrous casting, coated graphite and some ceramic materials have been studied. For the protective coating of graphite different approaches were taken such as plasma spraying, metallizing, vapor deposition and hot pressing, but most potential approach was the formation of diffusion bonded metallic carbide on the graphite surface with plasma sprayed zirconia layer as the final mold surface. Among all the ceramic materials examined, hot pressed boron nitride and also silicon nitride have shown considerable promise for permanent mold application.

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INTRODUCTION

This is the final report describing the work done at Abex Corporation under a program designed to develop a new technique for a machine casting process that will be practical and economically viable for ferrous alloys. Extensive effort has been conducted in industry prior to this program to develop a ferrous die casting process. All these programs have used existing types of die casting machines (i.e., shot chamber machines of the type used to die cast aluminum alloys). Their development work consisted of (a) minor modifications of the machine or process to permit pouring of steel, and (b) substitution of the shot chamber and die materials that will be more compatible with steel. These programs have not been very successful thus far. The major problem has been the materials that can withstand molten steel. The other minor but still important problems have been casting shrinkage and cracking.

A central conept of this research program is to develop a radically new technology and not make minor modifications of the existing processes. The emphasis of work at Abex was, therefore, on the development of a completely integrated furnace-valve-mold ferrous casting system that will produce quality steel castings in the five to twenty-five pound class more economically than is possible by present casting methods. The system will also produce high

casting speed and employ minimum metal handling. Our
efforts have been, therefore, directed in three major areas.

1. Design and fabricate an experimental melting and
    casting unit capable of examining several cast-
    ing process possibilities including casting of
    semi-solid alloys(rheocasting).

2. Determine the feasibility of a magnetohydrodyna-
    mic (MHD) valve to control and stop molten metal
    flow using laboratory scale equipment.

3. Develop a permanent mold for repetitive use in
    the automatic casting process envisioned.

EXPERIMENTAL FERROUS CASTING MACHINE

The design and fabrication of a pilot melting and
casting unit were undertaken with four specific objectives
in mind:

1. Evaluation of conventional vs. rheocasting process
    and development of system parameters for either or
    both approaches.

2. Determination of the mechanical properties of rheo-
    cast metals-cast iron and ultimately steel.

3. Evaluation of the design and materials of construc-
    tion in the casting unit and the mold, particularly
    those materials in close proximity to or contact
    with the molten metal.

4   Testing of an MHD valve should it become a feasible
    device.

    <u>Design</u> - The casting unit was designed on the basis
    of several fundamental requirements of the rheo-
    casting process as well as other features considered
    to be generally desireable for a conventional casting
    process.   The following are these basic requirements.

    1. The melting and casting operation should take
        place entirely under an inert atmosphere to
        minimize slag attack and other problems associ-
        ated with the presence of an air environment.

    2. The melt must be stirred continuously from the
        point at which the liquidus temperature is
        reached during cooling to the point at which
        the casting operation begins.

    3. The metal containing some predetermined frac-
        tion of solid must be moved rapidly and force-
        fully from the melting crucible into the mold,
        maintaining, as much as possible, the stirring
        action throughout the casting operation.

    Figure 1 shows the details of the Abex casting
    unit that was originally designed to meet these require-
    ments.   The materials from which the unit was constructed
    were as follows:

Component	Materials
Pressure Vessel (Figure 2)	Austenitic stainless steel weld fabrication.
Melting Unit (Figure 1)	Conventional induction melting coils with special support construction for mounting and bottom pour. Power - 100 KW Frequency - 3000 cps Source - MG Set
Bottom Plug (Fig.3)	Alumina
Plug Actuator(Fig.1)	Austenitic stainless steel
Drive Shaft(Fig. 4)	Austenitic stainless steel
Crucible (Fig. 5)	Alumina
Stirring Paddles (Fig. 6)	Alumina
Discharge Tube (Fig. 7)	Alumina

Drive Motor (not shown) Conventional DC motor of 3/4 H.P.

The drive shaft as shown in Figure 4 is water cooled and hence provided with cooling chambers for water circulation. The molds for the casting unit were made of graphite. In order to protect the graphite surface from oxidation and erosion by molten ferrous alloys, the mold walls were first chromized and then plasma sprayed with stabilized zirconia. This coating was selected as a result of our study of permanent mold materials to be discussed later in chapter 3 of this report.

The Abex standard test bars (#D14), shown in Figure 8,
were selected for casting to evaluate the performances of
the machine and the process. This bar design has been
used for many years by the Abex Experimental Foundry for
the evaluation of alloys and processes and its foundry
characteristics are well documented.

The rheocasting process for the experimental casting
unit is as follows:

1. With the chamber open, charge the appropriate alloys
   to the melting crucible with the paddles in the
   raised position and the plug in the sealed position.

2. Close chamber and flush with inert gas, nitrogen.

3. Melt down under slight positive pressure of nitro-
   gen gas.

4. Adjust temperature to just above liquidus, lower
   paddles into melt and begin stirring. The slots
   cut on the paddles and paddle-to-crucible clear-
   ance of 1/4" provide the shear required for rheo-
   casting.

5. Cool the melt to the appropriate temperature below
   the liquidus corresponding to the fraction solid
   desired. Since thermocouple cannot be inserted
   into the metal during stirring, the metal tempera-
   ture was read from the thermocouple inserted inside
   the crucible wall. This thermocouple was initially

calibrated against the temperature of the liquid
metal inside the crucible and intrapolated to tempera-
tures below the liquidus.

6. Pressurize the chamber to a positive pressure
   around 30 psi.

7. Pull bottom plug to cast into previously positioned
   mold. Mold was not evacuated.

This unit can process one 20 lbs. of ferrous casting in
each melting and casting cycle.

Fabrication - Figure 9 shows overall views of the
casting machine. The pressure vessel or the melt-
ing chamber is rigidly mounted on a steel frame-
work at a level that provides sufficient clearance
for the mold which was positioned directly under the
outlet. The latter is best seen in Figure 10. Manual
access to the chamber (other than by unbolting the
lid) is through the opening shown in Figure 10
immediately to the left of the name plate. In Figure
11, showing the rear of the chamber, the induction
power access port can be seen as well as the over
pressure burst disc installation. The presence of
this latter safety feature was considered an absolute
necessity in view of the unlikely but possible con-
tact of cooling water and molten metal. The disc

was designed to burst at just over 100 psi and provides 1.77 square inches of escape area should the occasion arises.

The induction power access port provides power to a centrally positioned induction coil in the bottom of the melting chamber (Figure 12). The induction coil receives an alumina crucible equipped with an alumina bottom pouring nozzle as shown in Figure 13. The nozzle passes through the bottom of the coil frame and out of the chamber through the bottom outlet shown in Figure 10.

The bottom pouring feature is accomplished by the bottom plug also shown in Figure 13. The taper at the plug bottom fits the taper at the top of the alumina nozzle, thus providing a seal similar to that normally used in small, bottom-pour ladles.

The stirring required by the Rheocasting procedures is to be accomplished by the paddle assembly shown in Figure 13. The paddles used were made of alumina. The rotation of the paddles is concentric with the bottom plug O.D., permitting totally independent operation of both.

The multi-component, water-cooled operating shaft for the paddles and bottom plug is shown out

of the assembly in Figure 14. The shaft consists
of a central solid non-rotating bar, which will
activate the bottom plug, an axially located tube
that provides the paddle drive, and a double-wall
axial water cooling sleeve. Figure 1 best shows
these details. The shaft was mounted in two bear-
ings that are attached to a vertically movable
support beam, and axially aligned exactly with the
central axis of the crucible. Figure 15 shows the
relationship among these components.

Vertical motion of the paddle assembly, re-
quired to move the paddles in and out of the cruci-
ble, is achieved by moving the support beam, guided
by two guide bars, using the air cylinder shown in
Figures 15 and 16. The upper end of the air cylinder
shaft is rigidly fastened to the main frame, thus
providing vertical motion of the entire support beam.

Rotational motion of the paddles was provided
by a motor attached to the rear of the support beam,
as shown in Figure 7.

Independent, short vertical displacement of the
crucible bottom plug was provided by a manually
operated locking lever device not shown here.

Operation - In order to provide a less severe thermal condition for preliminary operations, heats of 356 aluminum base alloy of m.p. 1225°F were made for casting. The details of the first experimental heat are as follows:

Wt. of the charge	- 10 lbs.
Power input for meltdown	- 25 KW
Casting process	- Conventional
Max. temperature of the melt	- 1400°F
Temperature of pouring	- 1350°F
Metal hold time	- 20 min.
Melting & casting atmosphere	- Air
Pouring	- Bottom pour, operated by stopper rod

The major problem encountered in this heat was the freezing of the melt in the nozzle (alumina tube of 0.5" I.D., 1.5" O.D. and 8" long) during pouring. The preheating of the nozzle seemed to be essential to solve this problem. Therefore, a 20 gage Nichrome wire was wound around the nozzle on the outside with a spacing of 6 turns to an inch for resistance heating. A ceramic insulation coating of Ultra-Temp 516 was used to protect the winding. The nozzle temperature was recorded intermittently during the heat.

Using the preheated nozzle, a second heat was made in the same manner as the first one. Just prior to pouring

when nozzle temperature reached about 900°F, the heating coil burnt out and the metal again froze in the nozzle during pouring. The burning was caused by excessive heating of the coil due to high current input (80 volts).

The next step taken was to increase the number of turns to 8 to an inch, use 22 gage wire and apply only 50 volts to the coil. By this a steady temperature of about 950°F was achieved inside the nozzle. A similar heat was made using this preheated nozzle. This time the pouring was successfully accomplished by using a chamber pressure of 5 psi.

A fourth heat was made in which the liquid metal was held in the furnace at 1300°F and the paddles were turned to 100 rpm and the chamber was pressurized to 20 psi. Several leaks in the chamber were detected and they prevented from building any higher pressure. This heat was successful.

The next heat was made for rheocasting. The details are:

Maximum meltdown temperature	- 1350°F
Temperature at which stirring was started	- 1250°F
RPM of the paddles	- 100 (approx.)
Power input during cooling (and stirring)	- 9 KW
Cooling rate during stirring	- 10°F/min.
Temperature of pouring	- 1190°F
Solid fraction at pouring	- 0.5 (approx.)
Nozzle temperature during pouring	- 950°F

This heat was successful. The micrographs
of conventionally cast and rheocast 356 aluminum
alloy are shown in Figure 18.

Several other problems were encountered during
the furnace operations for the above heats. There-
fore, it was decided to modify some of the designs
to solve these operational difficulties and make the
furnace more adaptable to ferrous castings.

Modifications - The problems encountered and the
corresponding design modifications made are discussed
below.

1. Although calculations have shown that the pre-
   heating of the nozzle was unnecessary, the
   frequent metal freezing became a serious problem
   during pouring. This was probably due to slow
   leakage and subsequent freezing of the metal
   in the nozzle during melting and stirring of
   the melt. In any case, it was decided to en-
   large the nozzle diameter and preheat the nozzle
   to about $2600^{O}F$ for ferrous castings. But, by
   using a resistance heating coil, a maximum of only
   $1200^{O}F$ was reached in the nozzle. Therefore,
   an induction heating was employed. Due to poor
   magnetic permeability of alumina nozzles, iso-

pressed high density alumina graphite refractory
nozzles were used instead. This is a proprietary
material made by Vesuvius Crucible Company and is
supposed to have higher resistance to oxidation and
erosion by metal than pure graphite has. For con-
venience, the crucible and the nozzle were made of
one piece as shown in Figure 19.

An induction coil of 5-1/2" diameter and 6"
length was used for preheating the nozzle. Since
both the melting coil (for the crucible) and the
heating coil (for the nozzle) were required to run
at the same time and the power input in these two
coils could not be controlled independently from
the same power supply (the power drawn by each coil
is dictated by the degree of magnetic coupling in
the coil), a separate power source (15 KW, 3,000
cycles MG set) was used for the heating coil. Since
it is convenient to enclose the heating coil in the
furnace chamber, the pressure vessel was redesigned
to accommodate the heating coil as shown in Figure 20.

2. Excessive leakage through several connections
   to the pressure chamber prevented building up
   of high pressure in the chamber. Use of better
   seals improved this pressure build-up. It was

found that a pressure of 20 psi in the chamber was sufficient for successful pouring during rheo-casting of up to 0.6 solid fraction. Therefore, the modified stainless steel chamber was rated for only 30 psi.

3. The lid of the pressure chamber appeared to be heated up by the radiation of heat from the molten metal. Since this heating could be severe during processing of ferrous metals, it was decided to water cool the lid. A water cooling jacket made of stainless steel was welded on the outside of the lid, as shown in Figure 20.

4. The high purity slip-cast alumina paddles supplied by Norton Company was found to be unsuitable due to their insufficient strength - there was frequent breakage problem. In their place, a set of closely spaced cylindrical alumina tubes was used for stirring the melt. These tubes are made by McDanel Refractory Company and used for thermocouple pro-tection tubes. In case of their failure, silicon-oxy-nitride paddles (made by Norton Company) would have been used instead. Since these stirring tubes undergo severe stress during stirring and their strength drops drastically around $2000^{\circ}F$, cylindrical graphite rods were inserted inside the tubes for rein-forcement. The graphite rods were fastened to the

stirring rod holder and the alumina tubes were
cemented on to the graphite rods as shown in
Figures 21 and 22. The exposed graphite surface
was given a protective coating to resist oxidation.

5. In one case the stopper rod broke during the melt-
down period. This was caused by the expansion of
the plug shaft since it was ridigly fixed at the
top end by a push-pull clamp device. In order to
allow for its free expansion, the plug shaft was
later attached to the push-pull clamp through a
flexible connector. By this arrangement the
stopper rod closed the nozzle by the weight of the
shaft and for pouring, it was pulled up by the
clamp.

   The stopper rods were also replaced by
McDanel's alumina tubes as shown in Figure 23.
These hollow tubes were filled with refractory
packing.

6. The resistance to shaft rotation was found to be
high. This was due to the shaft not being perfectly
straight and also the improper mounting of the
stationary water jacket around the shaft. This
problem was solved by improving all the shaft bear-
ings and redesigning the water jacket support system.

7. There was an occasion of rise of the liquid metal
in the clearance between the center shaft (for
operation of stopper rod) and outer shaft (for
rotation of the paddles) by capillary action.
This was caused by an excessive rise of the meniscus
of the liquid metal during meltdown. The entire
shaft assembly was, therefore, raised about 3" to
prevent any metal contact. This also brought the
paddle holder outside the induction coil and pre-
vented its unnecessary heating by the induction
field. This also necessitated longer stopper rod
and stirring rods.

8. The assembly for lifting the pressure vessel cover
and the shaft was modified to provide a smooth
lift with adjustable speeds and also to hold the
cover and the shaft in any intermediate position.
A larger air cylinder was installed and also the
brass bushings were replaced by linear ball bear-
ings for the sliding shafts.

9. A second sight port was installed on the pressure
vessel lid for lighting the inside of the vessel.
(See Figure 20).

10. Three guide rods were provided on the pressure
vessel to guide and align the vessel cover. (See
Figure 20).

11. One relief valve was installed in the pressure
     chamber.

12. Provisions were made for independent lifting of
     the cover, shaft and plug rod.

13. One thermocouple was installed inside the nozzle
     wall to record the nozzle temperature.

An overall view and a schematic drawing of the modified
furnace assembly is shown in Figure 24.

All the modifications were completed and the machine
was ready for casting. The level of confidence for success-
fully producing experimental castings from the machine was
high. However, after discussing the long term potential for
developing a full scale production process using the same
approach, it was decided that further work would not be in
the best interest of the objectives of the overall program.
Material and mechanical complications, not envisioned at the
outset of the program, strongly indicated that this approach
should be abandoned in favor of other approaches then under
consideration by other contractors.

It was disappointing to have placed the technical effort
into the Experimental Casting Machine and to abandon it before
producing even one ferrous casting. However, the decision
was recognized as being in the best interest of the overall
program.

DEVELOPMENT OF MAGNETOHYDRODYNAMIC (MHD) VALVE

This phase of the ferrous casting program calls for the investigation to determine the feasibility of using magnetohydrodynamic force as a valve to control and stop molten metal flow. This electromagnetic valve would circumvent many of the mechanical and material problems associated with existing pouring methods such as stopper rod valve, slide gate valve, etc.. The control or complete stoppage of flow can be accomplished by the magnetohydrodynamic countering of the force of gravity. The basic force in an MHD device can be expressed by

$$\vec{F} = \vec{J} \times \vec{B} \tag{1}$$

where F is the force experienced by the liquid

J is the current density

B is the magnetic flux density.

There are two kinds of MHD device of interest, (a) conduction type and (b) induction type. In the condition device, a direct current is applied through the liquid (in addition to a magnetic field applied in a direction perpendicular to that of the current), whereas, in the induction device, the current is induced in the liquid by an external induction field.

In a conduction cell the static support of a vertical column of liquid against the gravity is given by the relation,

$$JB = pgh \qquad (2)$$

where p is the mass density of the liquid

g is the acceleration due to gravity

h is the height of the liquid column

In an induction cell, on the other hand, the static re-support of a liquid column is given by,

$$B^2/2\mu_o = pgh \qquad (3)$$

where μ_o = 12.57 x 10^{-7} in MKS units.

On the basis of Equations 2 and 3, calculations have shown that the suspension of a sizeable head of molten iron is feasible by using magnetohydrodynamic forces. In the preliminary experiments of both conduction and induction type MHD valves of laboratory model, it was found that a reasonable lifting force could be generated by the MHD device but the major problem was the instability of metal-air interface, and therefore, a tendency for the valve to leak. The details of these experiments are discussed below.

Conductive Levitation - The set up for the conduction type experiment is shown in Figure 25. It consists of a plexiglass U-tube with a conduction pump installed in one leg. The cross section of the cavity is rectangular with 1.5" x 0.05" sides. Mercury was used as the liquid medium. Currents varying from 0 to 150 amps were applied along the long sides of the cavity and a

magnetic field of about 2,000 gauss was applied by a
permanent magnet along the short sides. The MHD
force generated thereby was vertical and was computed
by measuring the difference of the mercury levels in
the two legs.

The MHD force generated was found to be proportional
to the applied current as shown in Figure 26. The graph
also shows the theoretical force that was calculated
on the basis of uniform current and flux density. The
discrepancy is probably due to fringing of the electrical
and magnetic fields leading to non-uniform field densi-
ties and also energy lost due to heating of mercury.
This heating was, fortunately, very minor.

The stability of the mercury-air interface was
investigated by attempting to pump the mercury above as
well as below the electrode contacts. In both cases the
liquid surface was unstable.

It was realized from this experiment that a stronger
magnetic field was necessary for levitation of any practical
importance. Therefore, an improved conduction cell was
built (Figure 27) in which an electromagnet capable of
producing 4,000 gauss field and a circular cross section
tube with round insertable multiple electrodes (Figure 28)
were used. The circular geometry was selected because of
its conformity to a practical refractory nozzle. The test

of this apparatus indicated no appreciable difference in the lift obtained in the first experiment. This was due to considerable power loss in the electromagnet structure and, therefore, its inability to attain the design value of magnetic flux. The current required was approximately 40 amps per c.c. of mercury with 3.7 watts per c.c. at the electrodes.

Besides being insufficient the levitation force was also non-uniform in the liquid due to the discrete electrodes in this device. Therefore, a pair of long rail electrodes in combination with a pair of long electromagnetic poles were used to form a rail propulsion device. This is shown schematically in Figure 29. The molten metal is confined in the space between two conductive rail bus bars contacting the liquid and two long magnetic poles. When the current and the magnetic field are applied, the liquid experiences propulsion force along its entire length.

The electrodes were made hollow for cooling by the circulation of suitable coolant. The electrodes can be made of the same metal as the liquid in which case the electrodes become consumable but the extent of their melting can be controlled by controlling their cooling rate. The electrodes can also be made of any conductive

material of higher melting temperature and a conductive
refractory coating can be used on the electrode to pro-
tect from any corrosion or erosion. Alternating current
may be used in place of a steady current provided the phase
relationship between rail current and magnetic field is
time invariant. If the cross section of the nozzle is
made uniformly tapered toward the exit end, the magnetic
field will be more concentrated near the exit end, thus
providing a surface stabilizing action on the terminal
liquid surface.

Figures 30 and 31 show our laboratory model of
rail conduit hinged to the bottom of a furnace through a
cylindrical gate valve. The conduit can be set at differ-
ent angles with the furnace so that both pouring up and
pouring down are possible. In our experiment with
liquid woods metal, a metallostatic head of about 5" was
supported by applying 150 amp current and 1 kilogauss
magnetic field. It was calculated that 10 amp per cm^2
per gm per cm^3 per kilogauss is required to balance any
conductive medium against gravity.

Therefore, a much stronger current and magnetic
field are required in our model rail device to hold a
vertical column of any practical importance. It is worth
mentioning that the above rail propulsion device can also
be used for molten metal conveyance as an alternate to the
existing linear induction motor devices.

<u>Inductive Levitation</u> - Inductive levitation relies upon the coupling of energy from a primary coil into the melt as a one-turn secondary. In the induction type experiment woods metal was used in a 0.5" diameter pyrex tube. The current was supplied from a 10 KW, 610,000 Hertz power source into a 6-turn induction coil placed around the tube. Although the MHD force supported a small column of liquid, the metal trickled through at the center. The leak was probably due to the absence of any vertical force at the center. Therefore, for an efficient lifting of the liquid throughout the cross section we need an induced magnetic field that will produce stress fields with strong vertical components at all points. This can be achieved by using a conical induction coil that is capable of producing magnetic fields with strong horizontal components at each point in the liquid. The achievement of levitation has been obtained in the past through use of this type of tapered coil configurations.

Accordingly, we built a conical levitation coil assembly as shown in Figure 32. A copper plated ping pong ball was initially used for levitation. When resonated with 0.01 mfd at 17 kHz, the heating of the plating occurred without any levitation. No levitation could be achieved up to 150 volt-amp power. Aluminum

and copper discs and hoops of 1" to 1-1/2" diameter
were also tried for levitation, but the coil either
propelled or turned them on their ends, but did not
hold them levitated.

Besides generating a magnetic field with strong
horizontal component, the magnitude of induced current
and its penetration depth are equally important for
successful levitation. These factors are governed
by the frequency of the power supply. A higher fre-
quency field generates a stronger eddy current,
shallower skin depth and consequently more heating
and less levi:ation of the melt. An annular channel
will have higher levitation efficiency than a solid
cylindrical channel. The partitioning of levitation
and heating is also influenced by the power factor.
The primary coil can transfer maximum current for a
given voltage when it is tuned for unity power factor.
If the secondary is assumed to be reactive, its cur-
rent will be 90° out of phase with primary current
and there would be no levitation. If the secondary
is also tuned to resonance, a tremendous current would
flow and there would be no induction heating because
resistance is zero, yet, there would be levitation
because the currents are phased. There apparently
can be levitation without heating (at least cryogenically).

But how do you tune a slug secondary? Furthermore, the tighter the coupling (closeness to unity) the greater the mutual interaction between the coils and, therefore, they cannot be tuned independently.

For successful levitation, it is necessary to generate a large gradient of the magnetic field because the levitational force is proportional to and in the direction of the negative gradient of this field. This gradient field can be achieved by the divergent end effects in an induction coil. But this diverging magnetic field, while necessary, it not sufficient for the stable operation of the MHD valve which must be a servo system. By combining paired static levitation coils in a polyphase linear stator, wherein the molten charge in the nozzle will be a liquid rotor, we can obtain an MHD valve system adapted to treatment by servo theory.

The arrangement is shown in Figure 33 where coils are stacked axially to comprise a travelling wave stator coil of a linear motor. Interference with spatial wave length caused by coil dimensions in the stator system was solved by using mu-metal flux concentrators in our experimental model. Each coil is comprised of a mu-metal cup-core flux concentrator completely filled with a coil, except for a central bore. The mu-metal cores, when stacked, nest together to form a low reluctance magnetic path and an

aligned bore. Coils, available in sets of three,
have 15 turns of 1/8 inch copper tubing or 150 turns
of No. 18 enamelled wire. A 3-phase automobile
alternator was modified and used as the power source.
Unfortunately, only 225 volt-amperes could be generated
by this alternator in each coil type. The coils were
connected across A, B and C phases respectively for
3-phase levitation or an A, -B and C connection for
a partial, derived 6-phase connection. The latter
connection gives most efficient pumping.

Because of the power limitation of our 3-phase
generator and the inability to tune the equipment,
levitation only sufficient to raise solid conductors
was achieved. When an iron core was added to the
stator very strong levitation and propulsion of
aluminum tubing was obtained. Our model had a 150
to 1 turns ratio or a 15 to 1 turns ratio depending
on the coils used. Since the molten charge is one
shorted turn, the induction efficiency is very low.
A practical MHD valve without iron flux concentrators
must, from the standpoint of spatial frequency dimen-
sioning, be a single layer solenoid. The fundamental
problem is that of satisfying the contradictory require-
ments of making the volts-per-turn in a single layer
primary sufficiently high to ensure sufficient eddy

current induction in the melt for efficient levita-
tion force. This requires tuning the levitation
coils to resonance and the volts-per-turn of coil
not to be reduced by the loading of the melt below an
efficient levitational value.

Another method of levitation was also investi-
gated. The model is shown in Figure 34. This model
combines a rotating field with an ascending travelling
wave. A vortice pump is not the object here. Under
slip conditions the levitation forces on a liquid
would be static and hopefully will stabilize the lower
suspended surface. Lovell[1] first suggested the
rotating levitational field and Wroughton[2] et al
described its use for levitational melting and in con-
nection with surface stabilization stated: "The
resultant rotative fields, if multiple phase power
is used, conserves energy by reducing the effect of
the weak spot or "hole" in the magnetic field through
which the molten metal sometimes tends to be dis-
charged......effective rotation due to the phase
differences will tend to prevent discharge of molten
metal from the field when it is operated just above the
value needed for discharging the melt in order to con-
serve the energy". In the case of our model as applied
to the MHD valve, the rotating field is the 3-phase

equivalent of the single-phase ferrite stabilizer as
will be suggested later as our stabilizing approach. The
stabilizer has circular symmetry, the rotation of
which will provide an induced surface tension rein-
forcing field which will smear the lower surface with
"wiping" forces. The surface will probably not rotate
due to friction with the nozzle wall. Some levitation
has been achieved with this device but not enough
for practical applications.

Induction-Conduction Cells - Since it has been observed
in our experiments that a conduction cell is more
efficient in levitating liquid than an induction cell,
our next approach was to use a combination of conduc-
tion and induction cells in which most of the lift
would be provided by the conduction cell while the
induction field would stabilize the liquid surface and
provide some lift. A schematic diagram of the experi-
mental arrangement is shown in Figure 35. In this
case the liquid-air interface is stabilized by the
application of an RF field producing a transverse
magnetic field with a strong gradient.

Experiments were carried out with the fringing
field of a rectangular ferrite core and the results
showed that sufficient fields could be produced without
difficulty to levitate small copper and brass specimens,

but mercury and steel will require further effort.
At 20 kHz, only the large pieces would levitate; as
the frequency was increased, the smaller sizes would
float up. The mercury presented a problem because
of its high density, and required much higher field
gradients. The steel appeared to be just below the
levitating points as the frequency was raised to
50 kHz, but the breakdown voltage of the capacitors
was reached at this point. It seemed likely that an
improved larger core with suitable gap dimension and
a strong field gradient would be necessary for the
stabilization of mercury-air interface.

An alternative valve design was also proposed
and it is shown schematically in Figure 36. A con-
duction pump of circular channel having inserted
cylindrical electrodes would provide an accelerator
to hold back most of the head pressure. Around the
lower meniscus of the liquid metal column would be a
cup-core coil structure comprising a primary coil and
a lag loop coil for interface stabilization. While
only one coil element is shown having a lag loop, to
comprise a single phase levitator, two or three such
coil sections might be employed to expand to a two or
three phase pump.

The work on the development of MHD valve was
discontinued at this point because the entire effort
of this project was directed in the development of
ferrous casting machine.

DEVELOPMENT OF PERMANENT MOLD MATERIAL

The development of permanent mold is essential for making any casting process rapid and economical. We selected graphite and some ceramic materials for potential permanent mold application.

Graphite - Graphite has been considered by us to be the most suitable permanent mold material because of its low cost, easy machinability and above all its excellent thermal shock properties. The latter is particularly important in our ferrous casting system because of high casting temperatures involved. The thermal shock resistance of a material is expressed by the parameter μ as,

$$\mu = \frac{KS}{\alpha E}$$

where K is thermal conductivity

S is tensile strength

α is coefficient of thermal expansion and

E is modulus of eleasticity .

The higher the value of μ the better is the thermal shock resistance and graphite has higher μ than any other permanent mold material, both refractory metals and ceramic materials.

The main problem with the graphite is its poor resistance to oxidation and erosion by molten ferrous alloys. Therefore, our primary effort was devoted to developing a coating that will protect the graphite surface.

It has been observed in our previous works that the failure of all types of graphite protective coating occurs primarily by (a) cracking and (b) spalling or peeling. These are caused mainly by the following factors:

1. poor bond between the coating and graphite,
2. difference in the coefficients of thermal expansion of the coating and the graphite,
3. oxidation of graphite underneath the coating.

On the basis of these above factors the following graphite coatings were selected for evaluation:

1. Proprietary coating
   a. Ultra - temp 516
   b. Graphi-bond 551R
2. Plasma sprayed refractory oxide coating
3. Plasma sprayed refractory oxide coating chemically bonded with refractory particles mixed with the graphite
4. Diffusion bonded carbide coating with plasma sprayed refractory oxide layer as the final surface
5. Diffusion bonded carbide coating with diffusion bonded oxide layer as the final surface.

The types of graphite that were selected to evaluate different types of coating are:

a.   conventional graphite of varying coefficient
     of thermal expansion of the following types:
        i) extruded graphite from Union Carbide
           Co. (ATJ, ATL and AGSR grades)
       ii) molded graphite from Great Lake Carbon
           Co. (MHLM grade)
b.   Unicast molded-to-shape graphite from Unicast
     Development Corporation.

Before any coating was applied, the graphite sur-
face was sand blasted lightly with 80 mesh alundum
particles to achieve some mechanical bond with the coat-
ing.   The surface was then cleaned by heating the graphite
to about 350^OF and quenching in boiling water for about
2 min.   Finally, it was dried in oven at 300^OF for
about 30 min.

A simple mold was designed to evaluate most of the
coatings under actual casting conditions.   The mold had
a rectangular cavity of about 15 lbs. casting capacity.
Graphite formed the drag while the cope was made of
sand.   A simple step was provided on the graphite surface
to test how well the coating adhers to the corners.   All
the castings were made of various ferrous alloys poured
between 2300^OF and 2800^OF.

A detailed discussion of the coatings and the test
results are given below.

Proprietary coating

Ultra-temp 516 coating - This is a pro-
prietary coating made by Aremco Products, Inc.,
N.Y. This material is a high strength zir-
conia base ceramic adhesive (heat cure)
that can presumably withstand temperatures
up to 4400°F. The coating was applied by
brush in thin coats several times, each coat-
ing being followed by curing at 200°F for 2
hrs. The coating started to crack in some
areas during curing and also some reaction was
observed in the coating during pouring of the
metal.

Graphi-bond 551R coating - This is also a
proprietary coating made by Aremco. This is a
graphite base adhesive that can withstand
temperatures up to 5400°F in a reducing atmos-
phere. The coating was applied by brush in a
thin layer and cured at 250°F for 3 hrs. After
about eight castings the coating started to
appear spongy indicating either oxidation or
reaction with the metal has started.

Plasma sprayed oxide coating - On the basis of earlier
works at Abex, alumina (Metco 101) and magnesia
stabilized zirconia (Metco 210-NS) were considered

to be the best coating materials because they are thermodynamically most stable oxides and chemically most non-reactive to ferrous metals. We have examined:

a. single layer

b. double layer and

c. four layer graded coating.

a. A single layer coating of thickness about 0.006" was applied on the graphite surface by plasma spraying at 75 volts and 400 to 500 amps using Metco gun. The spray distance was 4" and nitrogen flow rate of 90 CFH, hydrogen flow rate of 20 CFH, carrier gas flow rate of 400 CFS and powder feed speed dial setting of 20 to 70 were used.

A visual examination of the graphite surface after the first casting showed that the coating spalled off in the gating area where the metal first hit the mold surface.

b. The above failure was believed to be due to poor bond between the coating and graphite. Therefore, the bond was improved by using a bond coat of NiAl (Metco 404) on the graphite surface. The bond coat thickness was about 0.002". This produced a slight improvement, the coating started to fail in the gating area after 2 to 3 castings.

c. Since NiAl and MgO-ZrO_2 have different coeffi-
cient of thermal expansion, it was then decided
to use compensating layers between the bond coat
and the final coat to absorb the thermal stress.
Two compensating layers were used (Figure 37),
the first one consisting of a mixture of 65%
NiAl and 35% MgO-ZrO_2 (Metco 413) and the
second one comprising of a mixture of 35% NiAl
and 65% MgO-ZrO_2 (Metco 412). The thickness of
each of these compensating layers was about
0.002".

This four layer graded coating produced a
great improvment. The coating lasted for about
12 castings after which the peeling of the graphite
surface was noticed in the gating area and also
near the edges of the step that was provided on
the graphite surface. The peeled off layer was
examined under microscope and was found to consist
of a layer of about 0.015" thick metal underneath
the coating as shown in Figure 38. It appeared
that the metal penetrated the coating at cracks
and spread underneath it. The void between the
coating and graphite was perhaps produced by oxi-
dation of the graphite surface.

<u>Plasma sprayed coating on ceramic infiltrated</u>

<u>graphite</u> - Our next approach was to improve the bond
between the graphite and coating by mixing graphite
with refractory particles of the same composition
or other that is capable of forming chemical bonds
with the coating material so that the coating will
be fusion bonded with these particles during plasma
spray.

There are several companies that manufacture
Al_2O_3 mixed graphite. We examined one sample from
Vesuvius Crucible Company and the material was found
to be not strong enough to be used as permanent mold
material. This poor strength was probably due to
poor bond between the graphite and Al_2O_3 particles.

We contacted Unicast Development Corporation
of New York who has a proprietary method of making
molded-to-shape graphite. They proposed that their
technique might be able to produce a strong graphite
refractory composite and the following three compos-
ites were made:

        a. NiAl mixed graphite

        b. Al_2O_3 mixed graphite

        c. MgO - ZrO_2 mixed graphite

About 10 to 12 volume pct of the refractory particles
of size -170 + 10 μ was mixed with graphite in each

case.   But, these graphite specimens also exhibited
poor strength and durability.   Moreover, the graphite
surface had a powdery appearance that prevented any
adherence with plasma sprayed coating.

Diffusion bonded carbide coating with refractory
oxide coating as the final surface - One of the prob-
lems associated with the plasma sprayed coating is its
inability to wet the graphite surface adequately and
thereby produce a good bond.   Therefore, it was
decided to change the graphite surface chemically so
that the subsequent ceramic coating will have a
better adherence.   The most convenient method was to
form metal carbides on the graphite surface since
carbon has good diffusivity in most of the metals.
The procedure is to deposit a thin metallic layer on
the graphite surface and then form carbide by
diffusion annealing.   By this the carbide layer will
be diffusion bonded to the graphite.   From thermo-
dynamic considerations we selected the following
three carbides:

> a.   Chromium carbide
>
> b.   Titanium carbide
>
> c.   Molybdenum carbide

a.   Chromium carbide - The chromizing of graphite
     samples was done by pack metallizing technique

at the Chromally Research, New York. The coat-
ing thickness was about 1 micron (4×10^{-5} in.). After
diffusion annealing at 2000°F for 1 hr. in a vacuum
surface, the graphite surface was found to contain
$Cr_{23}C_6$ by x-ray diffraction technique (see Table 1).
Two samples were prepared, one of them was coated
with a single layer of $MgO-ZrO_2$ (applied by plasma
spray) while the other was coated with 4 layer graded
$MnO-ZrO_2$ (Figure 37) using NiAl as the bond coat on
the carbide surface.

Table 1

Results of X-ray Diffraction Analysis

Coating Before Diffusion Annealing	Surface Constituents
Chromium by pack metallizing	$Cr_{23}C_6$
Titanium by pack metallizing	TiC - Major
	TiN - Major
	C - Major
	TiO_2 - Minor
Titanium by vapor deposition	C - Major
	TiO_2 - Minor
	Ti_4O_7 - Minor
Molybdenum by plasma spray	Mo - Major
	MoC - Minor
	γ -MoC - Minor

For evaluation of these coatings we used dip
test instead of pour test since dip test is faster
and less expensive. Although dip test and pour test
are not identical for mold evaluation, the thermal
shock resistance and mold-metal reaction can be
evaluated equally in both the tests. However,
in our case the dip test was used only for screening
purpose. The best coating was used in actual mold
for pour testing for final evaluation. Cylindrical
samples of 2-1/2" dia. x 8" length with insertable
steel rod at one end was prepared for the dip test.
The test arrangement is shown in Figure 39 where
A is an induction furnace containing molten cast
iron (C-3.5% and Si-2.00%) at a constant temperature
of 2350°F with power on, B is a cylindrical steel
chamber with the bottom open and top covered with
a transite lid, C is the cylindrical specimen that
is suspended by a handle bar at one end and inserted
into the chamber through its lid, and D is the gas
port that leads argon gas into the chamber to flush
it continuously. This inert atmosphere was maintained
to prevent any slag formation. A gap of about 2"
was provided between the metal surface and the
bottom of the chamber for the outlet of argon. The

specimen was dipped into the metal by about 5" and held there for several seconds until the surface reached the temperature of the melt. It was then pulled out and allowed to cool to about $1000^{O}F$ and then dipped again. This cycle was repeated 10 times before it was cooled to room temperature for visual examination. The results of the dip tests are shown in Table 2. As can be seen the 4 layer graded coating of $MgO-ZrO_2$ survived 50 cycles of dip test whereas the single layer coating started to fail after about 40 cycles.

The specimen with four layer graded coating was later dip tested in liquid steel at $2950^{O}F$, but after about 3 cycles the coating started to fail. The failure seemed to have occurred due to partial melting of NiAl. The melting point of stoichiometric NiAl is only $2980^{O}F$ and our NiAl powder contained off-stoichiometric composition of lower m.p.

b. <u>Titanium carbide</u> - Several procedures for coating graphite with titanium were investigated of which the following two methods were selected:

        i) Vapor deposition

       ii) Pack metallizing

Vapor deposition of titanium was done at AMMRC (Army Materials and Mechanics Research Center), Massachusetts

DIFFUSION BONDED CARBIDE COATING

Mo-carbide
by plasma spray

4 layer ZrO_2
(started to fail
around 50 cycles)

1 layer ZrO_2
(fairly good
after 50 cycles)

Pack metallizing

4 layer ZrO_2
(started to fail
around 30 cycles)

1 layer ZrO_2
(started to fail
around 30 cycles)

Ti-Carbide

Cr-carbide
by pack metallizing

4 layer ZrO_2
(still good after
50 cycles)

1 layer ZrO_2
(started to fail
around 40 cycles)

Vapor deposition

4 layer ZrO_2
(started to fail
around 10 cycles)

1 layer TiO_2
(started to fail
around 20 cycles)

Table 2

by vaporization of pure titanium wires under
vacuum. Pack metallizing was done by Chromally
Research, New York by packing graphite specimens
with titanium powder and carrier gas in a closed
crucible and heating at around $2000^{\circ}F$ inside a
furnace. The coating thickness in each case was
about 1 micron. The specimens were diffusion annealed
at $2000^{\circ}F$ for 1 hr. in a vacuum furnace and the results
of x-ray diffraction analysis of the surface are shown
in Table 1. As can be seen the vapor deposition
technique was not successful due to formation of ex-
cessive oxide and no carbide. Moreover, it is an
extremely slow process. In titanizing process, how-
ever, there was formation of some TiN along with TiC
on the surface. The appearance of strong carbon lines
in the diffraction pattern indicates that the carbide
layer was very thin. Several experiments were run to
minimize the formation of TiN but were not very suc-
cessful. Since TiN has a very high melting point we
considered its presence to be not harmful. Two samples
were prepared by vapor deposition technique, the one
coated with single layer TiO_2 lasted about 20 cycles
and the other one coated with 4 layer graded $MgO-ZrO_2$
lasted only 10 cycles. On the other hand, two samples
were prepared by pack metallizing technique, one was

c. <u>Molybdenum carbide</u> - Since no successful pack
    metallizing process exists for molybdenum so far,
    it was deposited by plasma spraying (about 0.001"
    thick) and molybdenum carbide was formed by diffu-
    sion annealing at 2000°F for 1 hr. in a vacuum
    furnace.   The plasma spraying of Mo was done in the
    air since the extent of oxidation of Mo during plasma
    spraying was only about 5%.   The x-ray diffraction
    analysis showed that the conversion of Mo to its
    carbide (Table 1) on the graphite surface was
    difficult by diffusion annealing.

    Both the single layer MgO-ZrO$_2$ specimen and 4
layer graded MgO-ZrO$_2$ specimen lasted about 50 cycles
of dip test.   These specimens were later dip tested
in liquid steel at around 2950°F and the coating
started to fail after about 3 cycles.   This failure
appeared to be due to melting of the bond coat NiAl.
Therefore, the 4 layer graded MgO-ZrO$_2$ coating on Cr-
carbide surface performed best in the dip test.   This coat-
ing was subsequently evaluated by pour test in graphite
molds since dip test was a severe test and in actual
casting conditions the maximum temperature the graphite
mold wall reaches is substantially less than that of the
liquid metal.   Small pig molds of graphite with 5"x3"x2"
mold cavity were made and the entire surface was chromized
by pack metallizing technique.   An x-ray diffraction

analysis revealed that $Cr_{23}C_6$ was already formed on the graphite surface by the metallizing treatment. Therefore, no diffusion annealing was done for these molds. One mold was given a coating of $MgO-ZrO_2$ with a bond coat of NiAl whereas the other was given four layer graded $MgO-ZrO_2$ coating using NiAl as the bond coat. During plasma spraying some problems were encountered, an excessive amount of coating material was found to accumulate around the corners leading to a non-uniform coating in these areas. Liquid steel was poured in the mold cavity at around $3000^O F$ and after about 3 castings the coating started to spall around the corners in both the molds. The coating seemed to have separate at the $Cr_{23}C_6$-NiAl inter-face, It is likely that during plasma spraying of one side of the mold cavity, the adjoining sides received some "overspray" which was normally not very adherent and this resulted in a failure of the coating in these areas.

Studies were made to see if the castings could be made against the chromized surface without using any subsequent plasma sprayed coating. Although $Cr_{23}C_6$ is dissolved in liquid steel to some extent, it is possible that the metal next to the mold surface might solidify immediately on contact with the mold wall (except in the gating area) and cause negligible amount of mold erosion. But the coating failed after about 6 castins due to the coating-to-metal reaction.

Pour test was also conducted on titanized (by pack
metallizing) and plasma sprayed surface. Since x-ray dif-
fraction analysis of the titanized surface showed the absence
of any residual titanium, no diffusion annealing was per-
formed on these titanized molds. Two molds were titanized,
one was coated with $MgO-ZrO_2$ using NiAl as the bond coat
and the other with four layer graded $MgO-ZrO_2$. The plasma
spraying was done carefully so that no additional deposit
from "overspray" is formed. The coating in both the molds
lasted for about 10 castings before the corners started to
spall. It seemed that the coating life can still be enhanced
by careful plasma spraying.

Diffusion bonded carbide coating with diffusion bonded
oxide layer as the final surface - The next step taken
was to improve the bond between the carbide surface and
the oxide coating by forming diffusion bonds between the
two (Figure 37). This was accomplished by plasma spraying
a pure metal on the graphite surface and then diffusion
annealing in a controlled oxidizing atmosphere. A diffu-
sion bonded carbide layer was formed at the graphite sur-
face and a diffusion bonded oxide layer on the carbide
surface to form the final surface. From thermodynamic
considerations titanium was selected as the coating
material. Pure titanium powder was plasma sprayed under
vacuum (done by General Plasma Associates, Conn.) to a
thickness of about 0.01" on the graphite surface and the

carbide-oxide layers were formed by diffusion
annealing the specimen at $1400^{\circ}F$ for 4 hrs. in a
controlled oxidizing atmosphere. The evaluation of
these specimens was not completed before termination
of the project.

Ceramic Materials

Besides graphite, the following hot pressed ceramic
materials were also studied for permanent mold applica-
tion:

a. Silicon nitride (from Norton Co.)

b. Zirconium diboride (from Carborundim Co.)

c. Boride "Z"   ("   "   ")

d. Boron nitride   ("   "   ")

e. Modified ZRBSC-D   (" Norton Co.)

All these materials were evaluated by pouring ferrous
metals in the temperature range of $2400^{\circ}F$ to $2700^{\circ}F$ in
open ended cylindrical sand molds using these specimens
as chill plates. Zirconium diboride and boride "Z"
specimens were small and they were embedded in a sand
mold of simple rectangular cavity. No preheating of the
specimens were done. Some of these materials were tested
in both coated (with single layer $MgO-ZrO_2$) and uncoated
condition but the coating in each case started to fail
within 5 castings. Silicon nitride (uncoated) showed an

extremely slow reaction with the metal before it
shattered into pieces during the eighth casting indi-
cating its insufficient thermal shock resistance.
Zirconium diboride showed an extremely poor thermal
shock resistance and cracked during every pouring.
Boride "Z" showed some cracking and reaction with the
metal. Boron nitride showed good results; although it
showed slight reaction with the metal, it did not
crack at all in a total of 16 castings.

ZRBSC-D is a hot pressed ceramic mix of zirconium
boride and silicon carbide that is capable of withstand-
ing high temperatures. The thermal shock resistance
of this material is presumably very good but it has been
demonstrated in other works that the material shows some
reaction with the ferrous metals. Therefore, two
different modifications were made to reduce the mold-
metal reaction,

    1. mixing of CaO stabilized ZrO_2 with ZRBSC-D

    2. hot pressing a surface layer of CaO stabil-
       ized ZrO_2 onZRBSC-D.

Three different mixes were tried, 29, 19 and 13 vol.
pct. of $CaO-ZrO_2$, to reduce the mold-metal reaction
without impairing its thermal shock resistance. Circu-
lar discs of 4" dia. and 3/4" thick were made. On

examining these samples in the as-pressed condition it was found that the disc with 29% $CaO-ZrO_2$ was very seriously crazed cracked probably due to significant shrinkage because of reaciton of zirconia with the balance of the mix. However, all the discs cracked immediately after the metal was poured suggesting their very poor thermal shock resistance for our application.

Since mixing of zirconia was contributing to the poor thermal property, attempts were then made to hot press thin layers of graded $CaO-ZrO_2$ on ZRBSC-D surface. A three layer graded coating of increasing $CaO-ZrO_2$ content (each layer of about 0.003" thickness) was originally planned to compensate the difference in the thermal expansions of the substrate and zirconia, but this could not be accomplished by Norton's existing facilities. Instead, just one layer of $CaO-ZrO_2$ of about 0.03" thick was hot pressed on ZRBSC-D substrate.

Problems were encountered in selecting the hot pressing temperature because of large difference in this temperature for $CaO-ZrO_2$ and ZRBSC-D. However, the problem was finally resolved and two hot pressing temperatures were selected. When cooled to room temperature after hot pressing, the samples showed numerous cracks in the zirconia surface layer probably because of difference in the thermal contractions of the substrate and

the surface layer. The surface layer was ground off from the substrate and an x-ray diffraction analysis of this layer showed some preferential diffusion of ZrB_2 into $CaO-ZrO_2$. It was noticed during surface grinding that the bond between the substrate and the surface layer was very good in some areas and poor in others. However, considering the difficulties encountered in hot pressing operation and the cracking problem of the surface layer, this concept was abandoned for making permanent molds.

Therefore, among all the ceramic materials studied in this program, boron nitride produced the best results, but the material and processing costs were considered to be extremely high. Silicon nitride shows some promise if preheating will ameliorate the poor thermal shock resistance.

CONCLUSIONS

1   The experimental ferrous casting machine designed and
    built in this program appeared to be at least partly
    successful for both conventional and rheocasting
    process.   But due to the complications in its construc-
    tion and operation this design may not be practical for
    full scale production.   Material still remains a major
    problem for ferrous casting.   Instead of batch type
    operation as in this case, a continuous type process
    would be more economical.

2   The use of MHD valve for controlling metal flow in
    foundry applications seems highly questionable due to
    enormous power requirement, excessive heating of the
    metal, metal-air interface instability, etc.   However,
    for a laboratory scale model its successful operation
    can be demonstrated.

3   For permanent mold application of graphite for ferrous
    casting, diffusion bonded carbide coating (by metalliz-
    ing and/or diffusion annealing) is better than other
    coating techniques.   The major problem of ceramic
    materials was their poor thermal shock resistance.
    Among the limited number of ceramic materials tested in
    this program, boron nitride appeared to have the best
    thermal shock resistance.   Also its reaction with the
    ferrous alloys was very slow.

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PLUG ACTUATOR
DRIVE SHAFT
WATER JACKET
INDUCTION COIL
CRUCIBLE
VESSEL
PADDLE
PLUG
DISCHARGE TUBE

AMX MANUFACTURING RESEARCH AND DEVELOPMENT
MAHWAH N J 07430

FURNACE & VESSEL
ARRANGEMENT

| MATERIAL | | EST WEIGHT RAW FIN | SCALE = 1" | SHEET OF | DES | DR J.M. | CK | DATE | D |
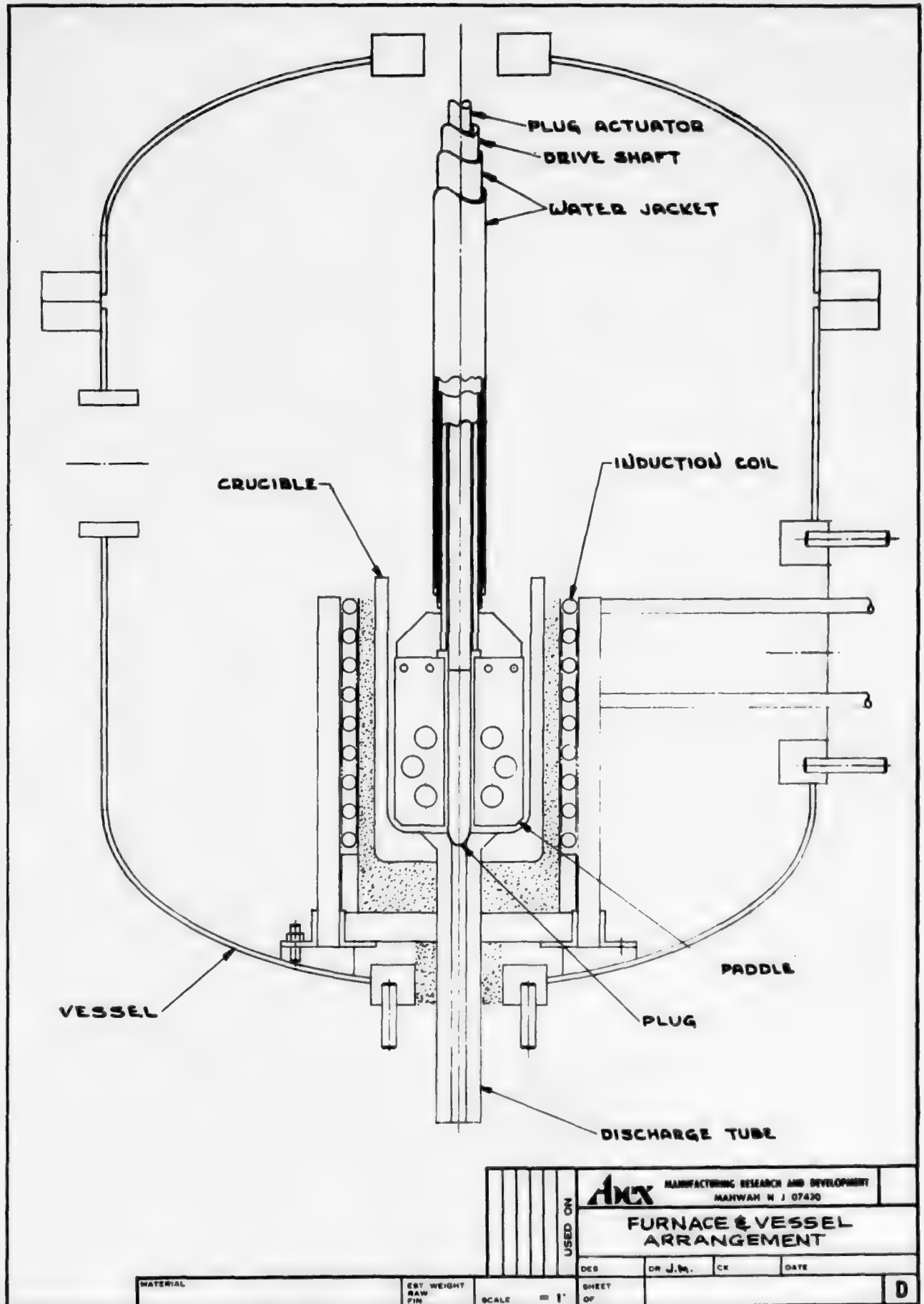
Figure 1. Furnace and Pressure Vessel Arrangement.

Figure 2. Pressure Vessel.

Figure 3. Stopper Rod.

Figure 4. Drive Shaft.

Figure 5. Crucible.
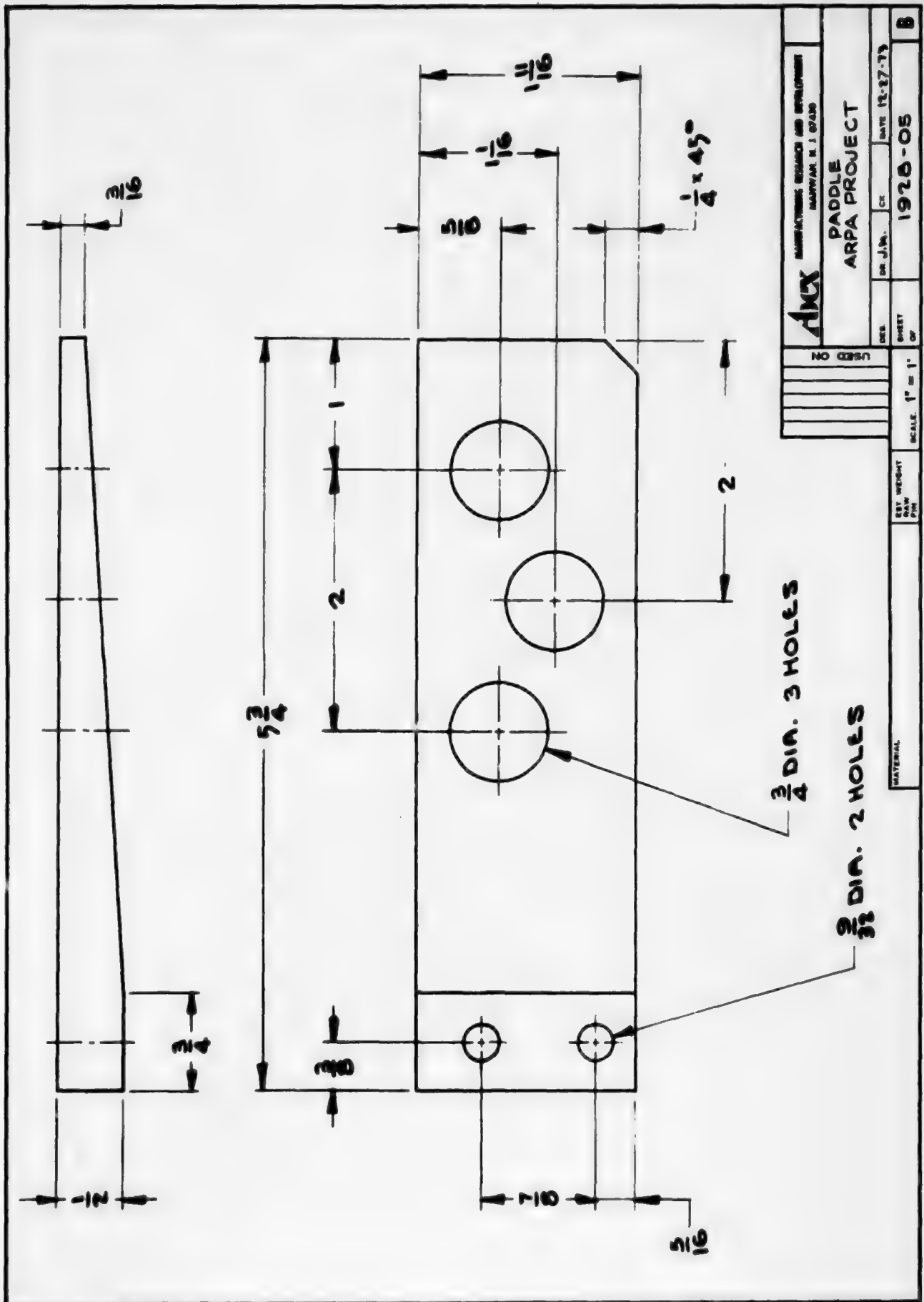
Figure 6. Stirring Paddles.

Figure 7. Discharge Tube.
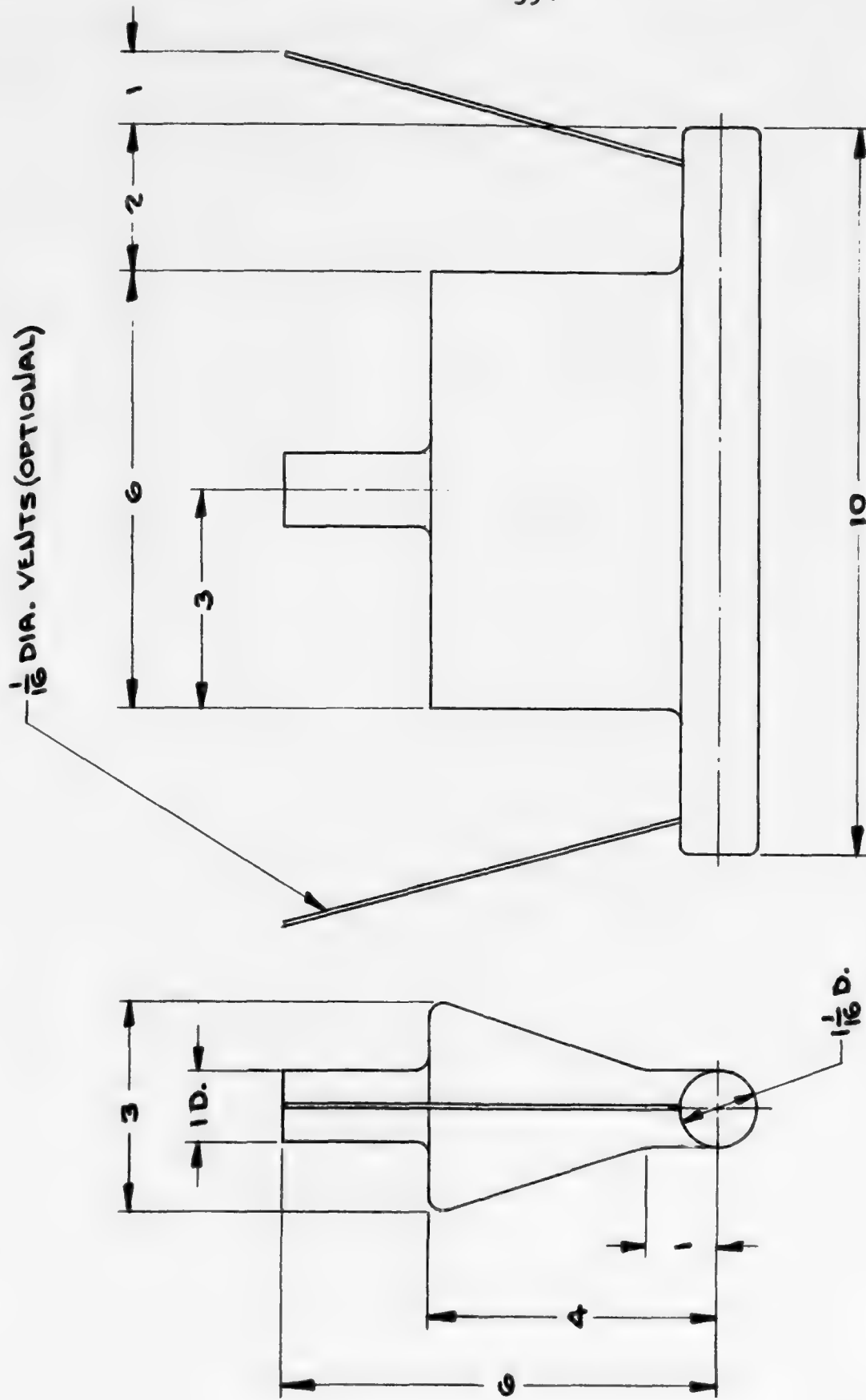
Figure 8. Abex Test Bar (D14)
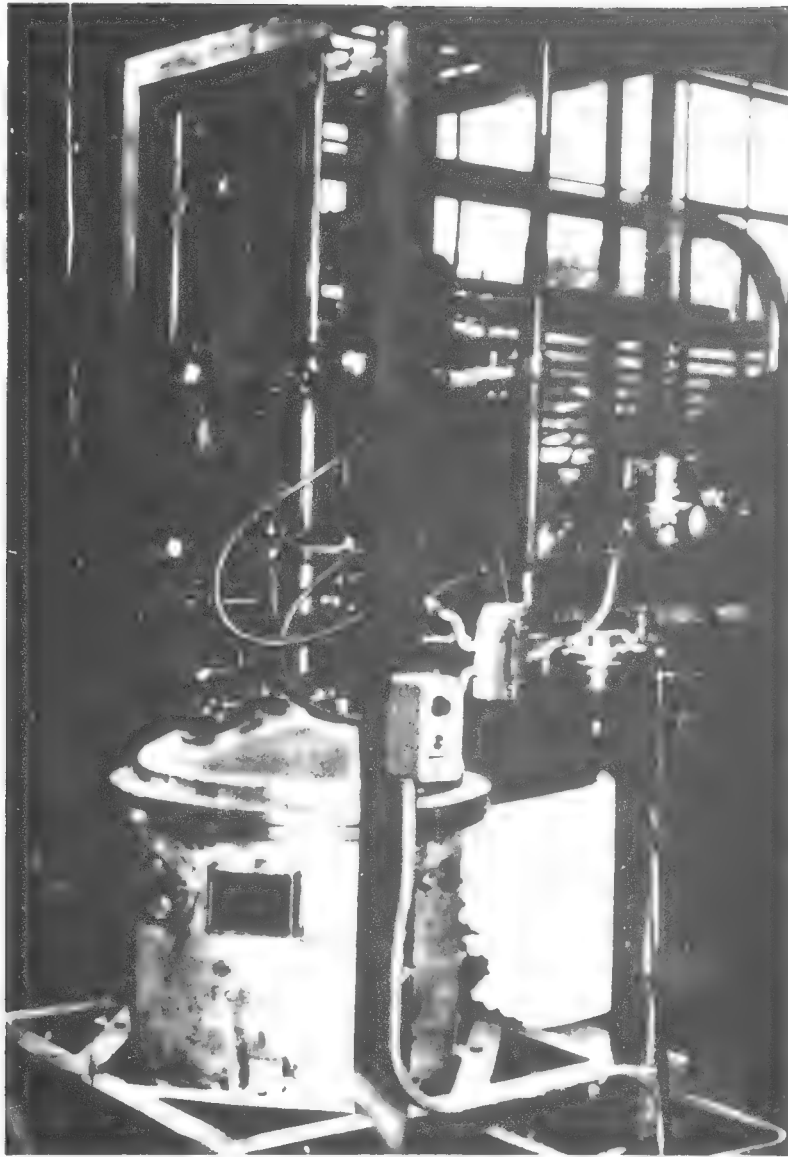
Figure 9(a) Experimental Melting and Casting Unit
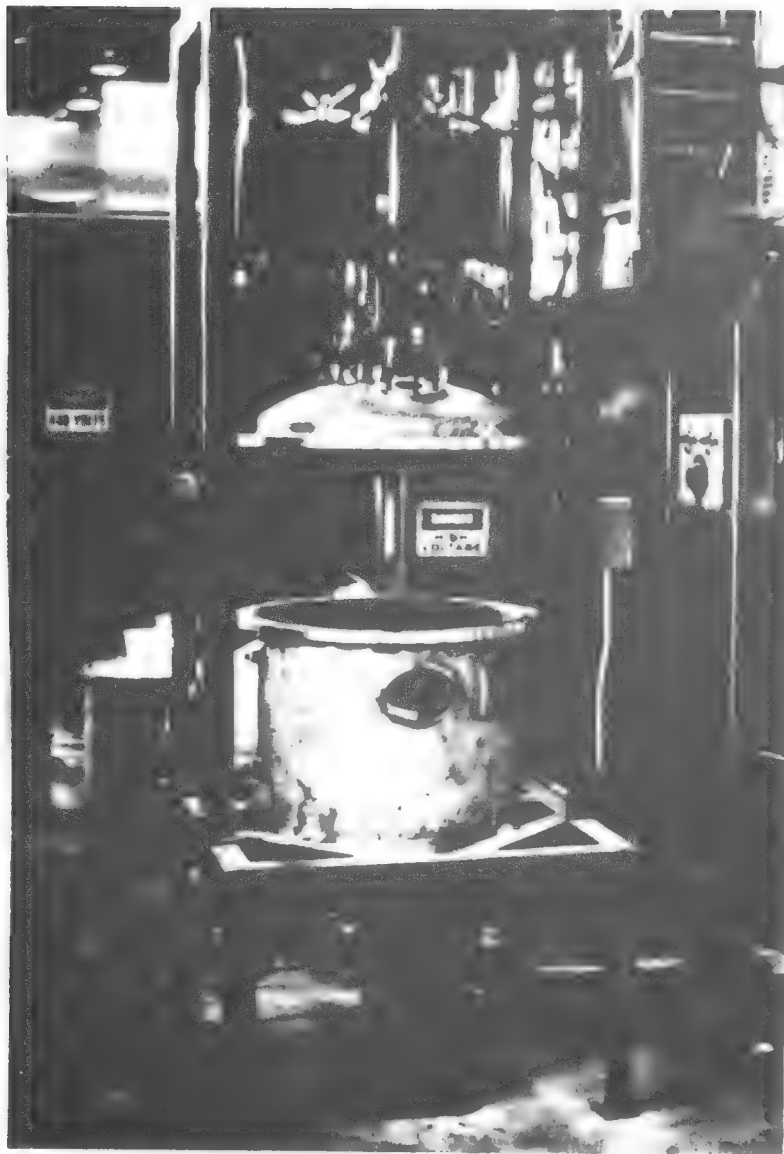
Figure 9(b) Experimental Melting and Casting Unit
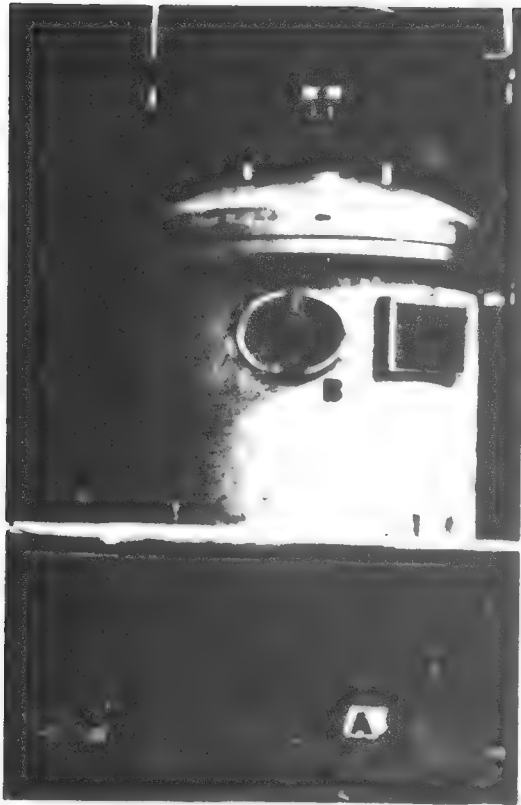
Figure 10.

Front View of Casting Unit

A Outlet

B Access Port

Figure 11.

Rear View of Casting Unit

C Induction Power Port

D Burst Disc Fixture
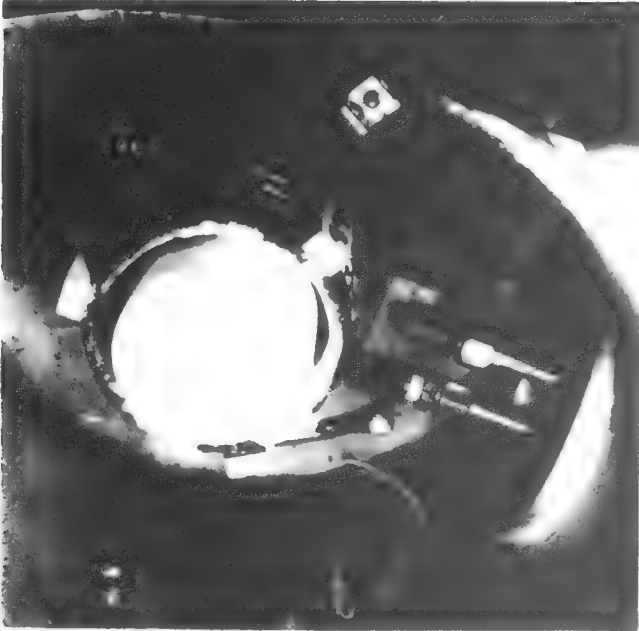
Figure 12.

Induction Coil With Crucible
in Place

Figure 13.

Refractory Components of
Casting System

A   Alumina Crucible
B   Bottom Nozzle
C   Bottom Plug
D   Paddle Assembly
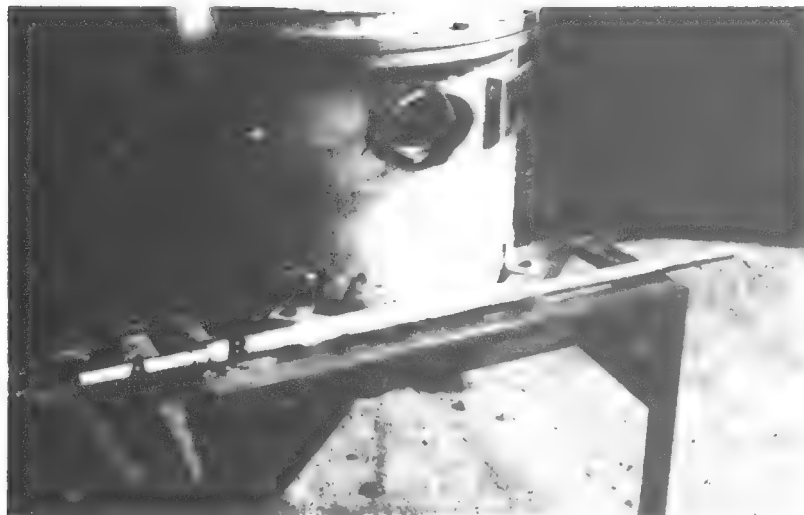
Figure 14.

Multiple-Function Shaft

A Paddle Drive
B Cooling Jacket
    (Note: Plug Actuating
    Bar Not Shown)
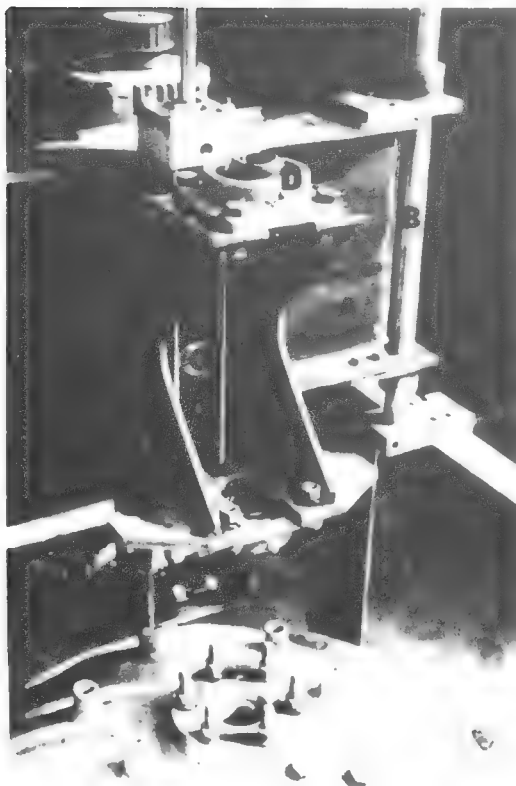
Figure 15.

Shaft Actuating Assembly

A   Support Beam
B   Guide Bars
C   Air Cylinder
D   Shaft Bearings
E   Paddle Drive Motor
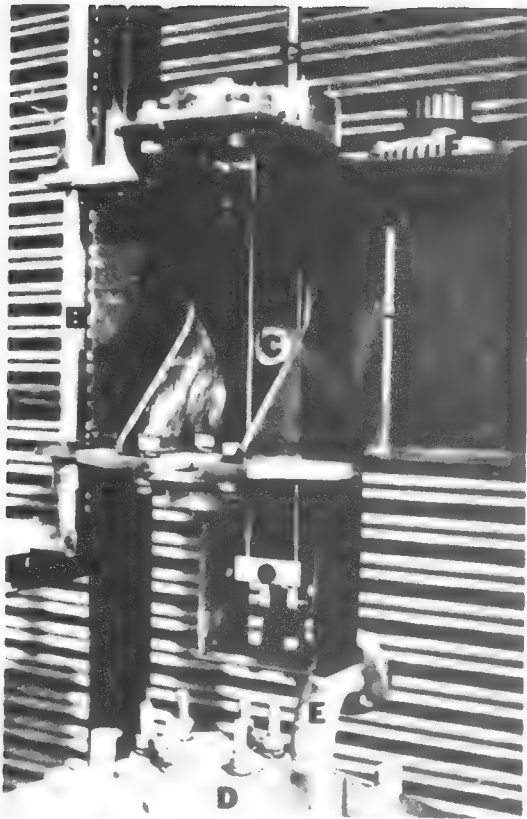
Figure 16.

Shaft Actuating Assembly
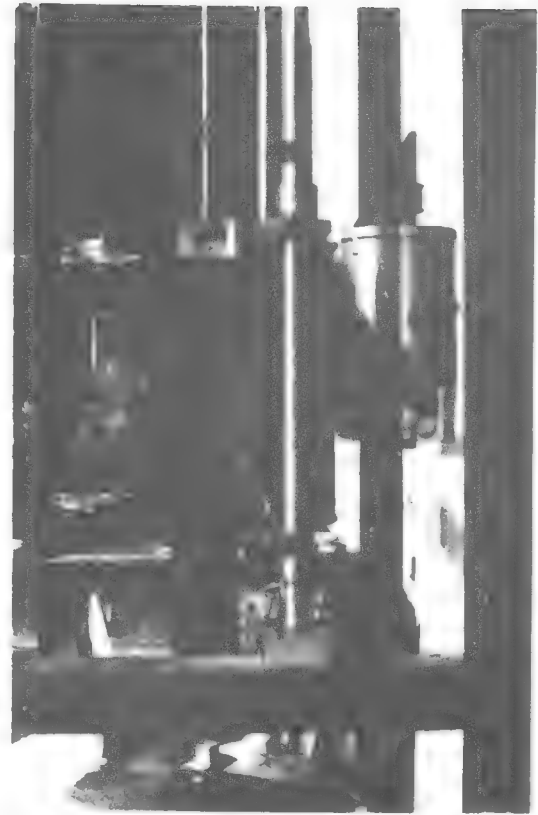
Figure 17.

Shaft Actuating Assembly

A   Support Beam
B   Guide Bars
C   Air Cylinder
D   Casting Chamber Access
E   Burst Disc Fixture
F   Paddle Drive Motor
G   Fixed Air Cylinder Shaft
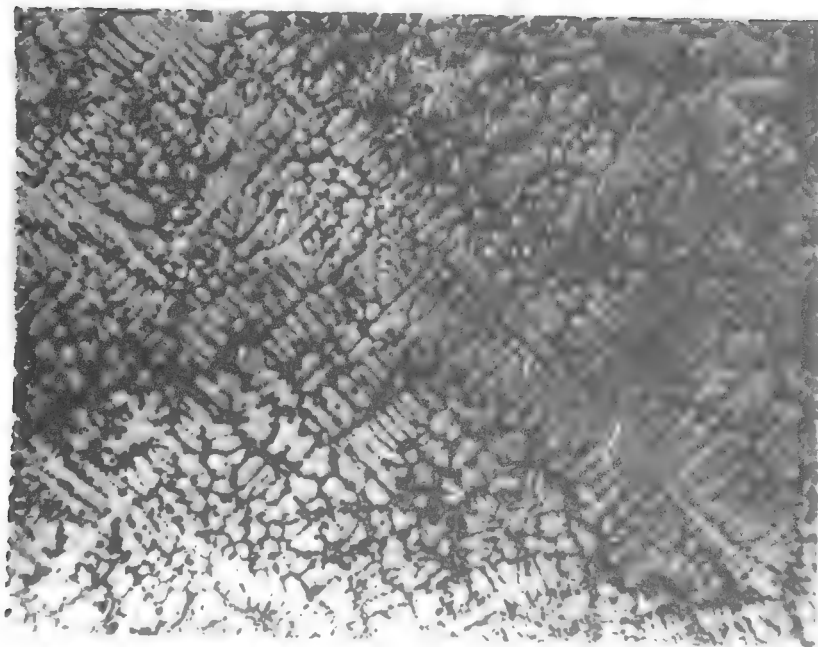
AW116701   50X

(a)   Conventionally Cast
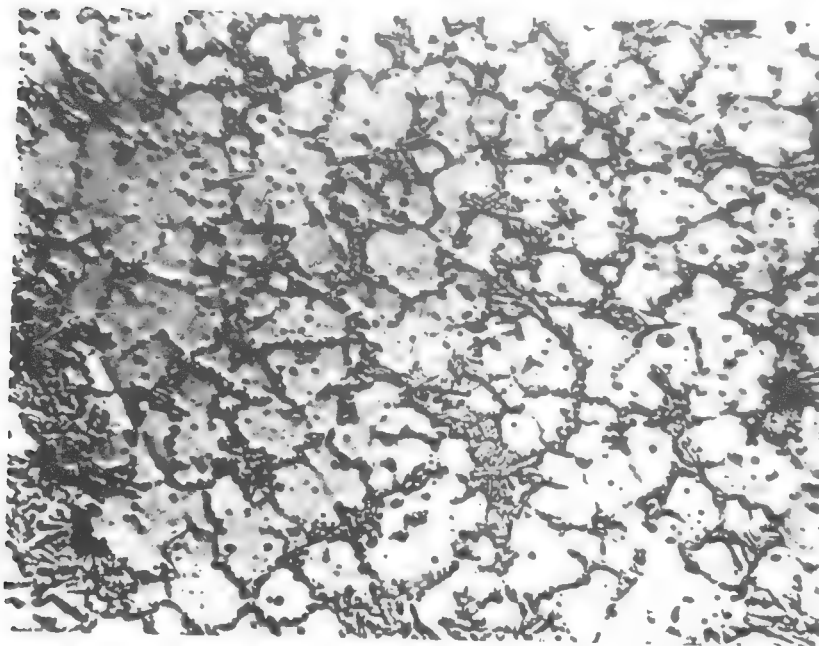
AW116601   50X

(b)   Rheocast at About 0.5 Solid Fraction

Figure 18.   Micrographs of Conventionally Cast and Rheocast
356 Alumina Base Alloy (Al-7% Si).

Figure 19. Modified Crucible.

Figure 20. Modified Pressure Vessel.

Figure 21. Stirring Rod and Assembly.

Figure 22. Stirring Rod Holder.

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Figure 23. Modified Stopper Rod.

Figure 24(a). Modified Furnace and Pressure
Chamber Assembly.
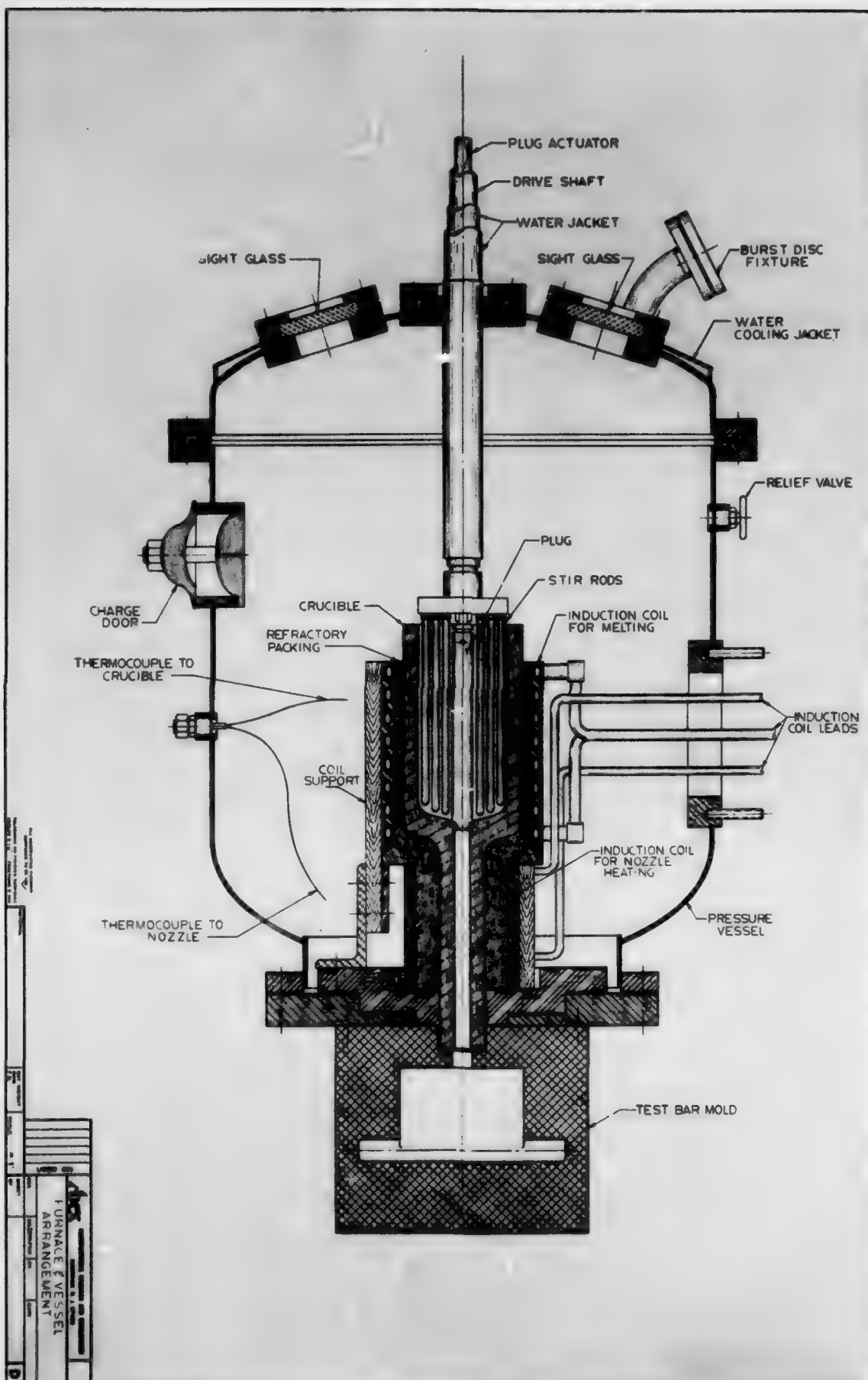
Figure 24(b). Modified Furnace and Pressure
Chamber Assembly.
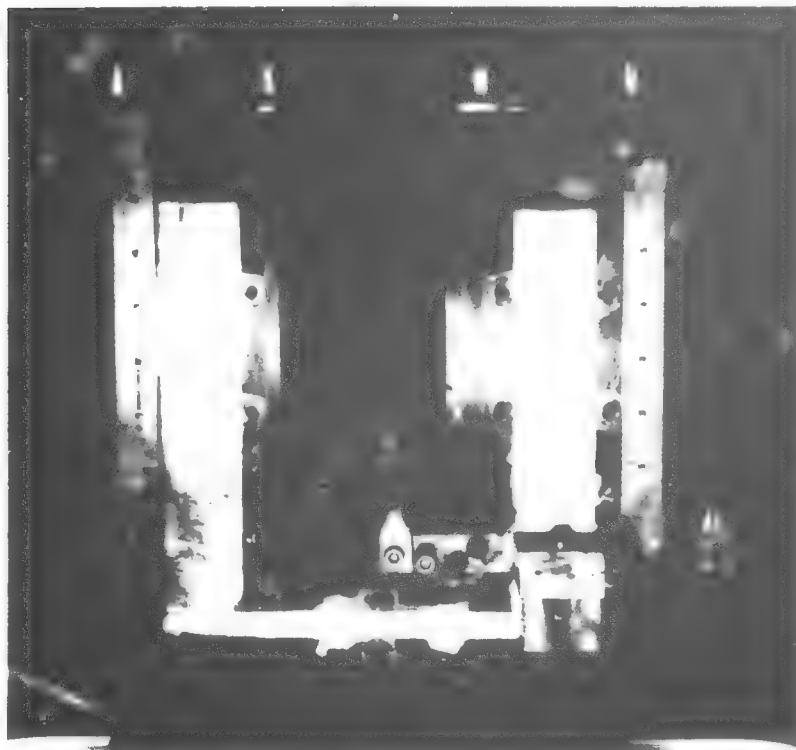
Figure 25.   MHD Conduction Pump.
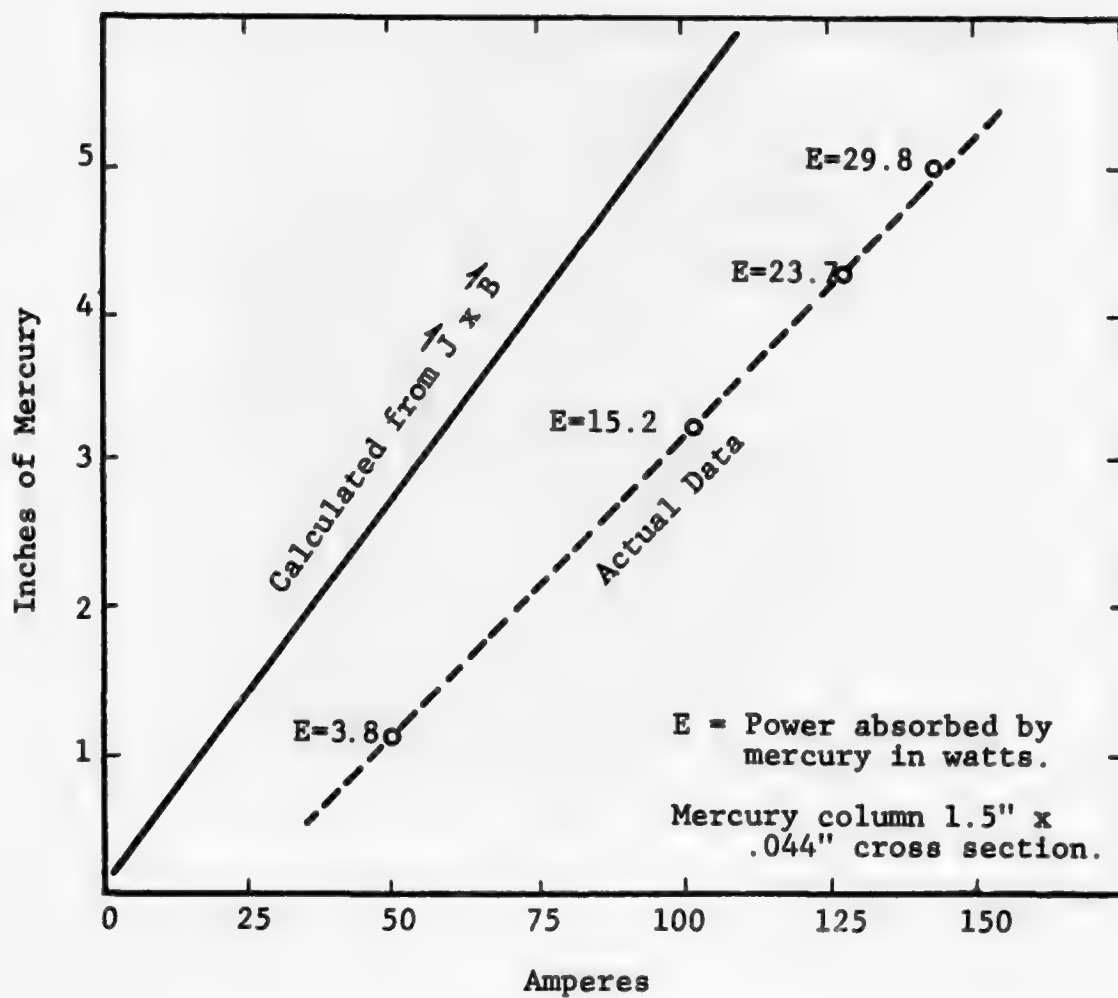
Figure 26. Theoretical and Actual Performance of Conduction Pump.

Electromagnet Assembly

Tube Containing Mercury
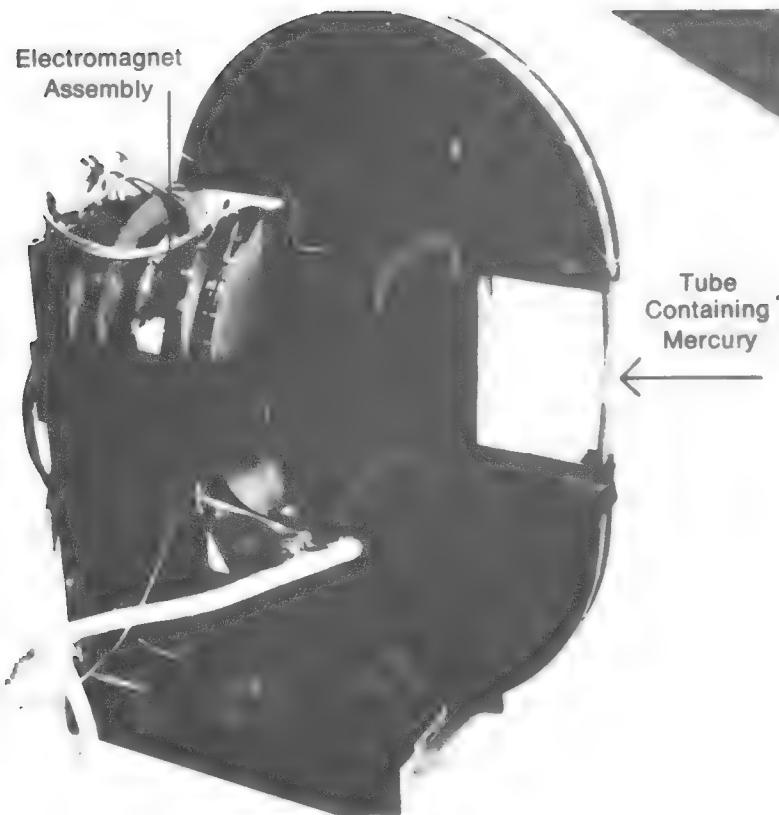
Figure 27.   MHD Conduction Cell Electromagnet.
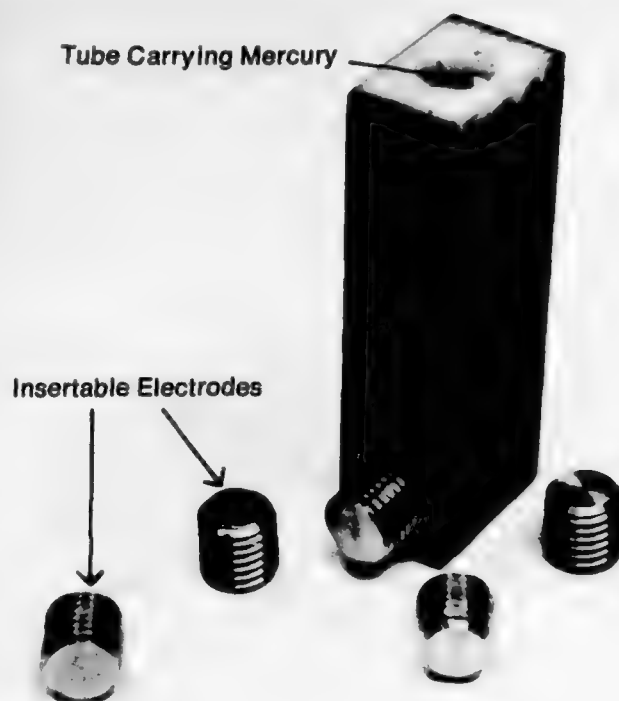
Figure 28. Multiple Electrode Assembly.
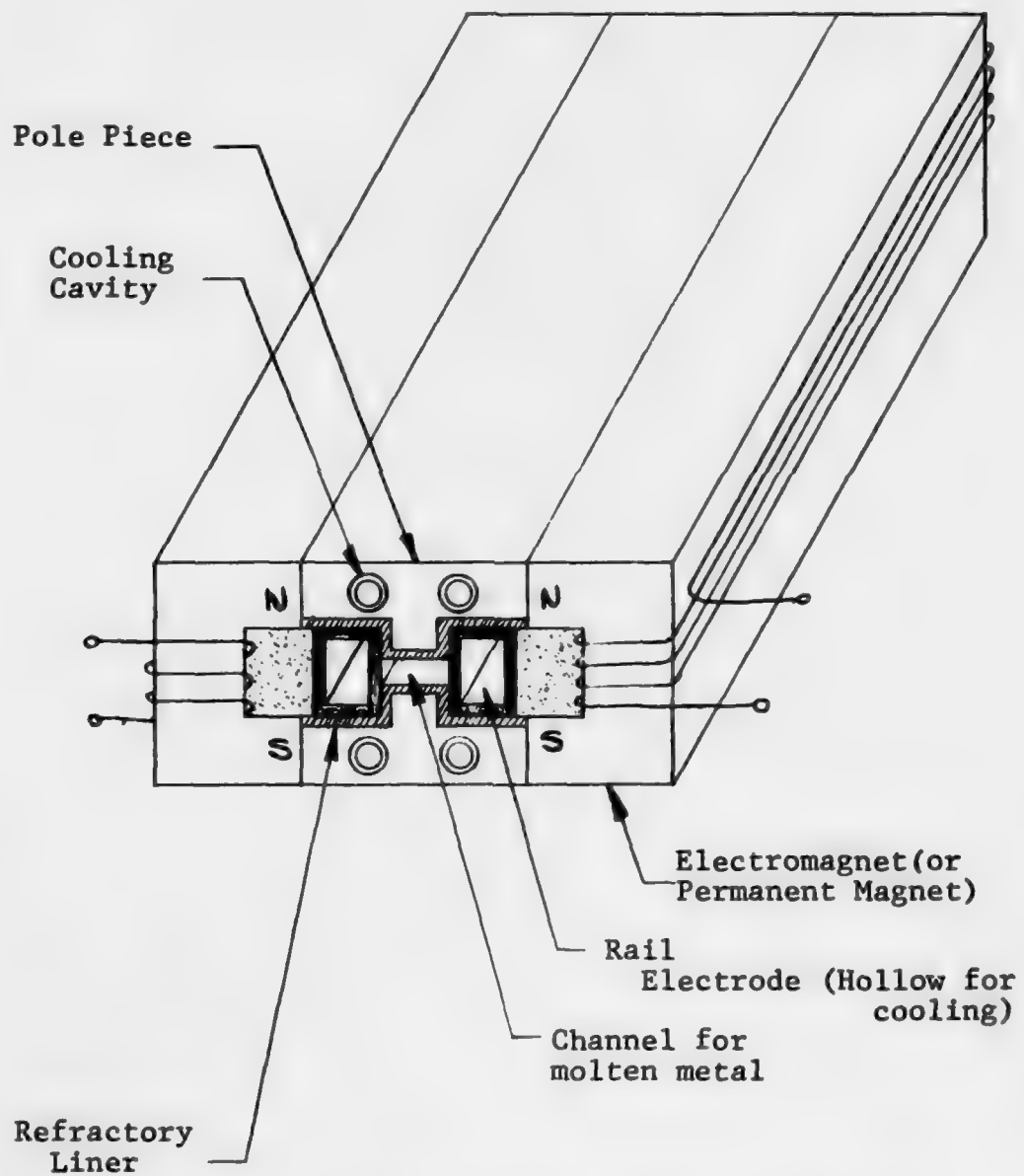
Figure 29, Rail Propulsion Conduit and Valve
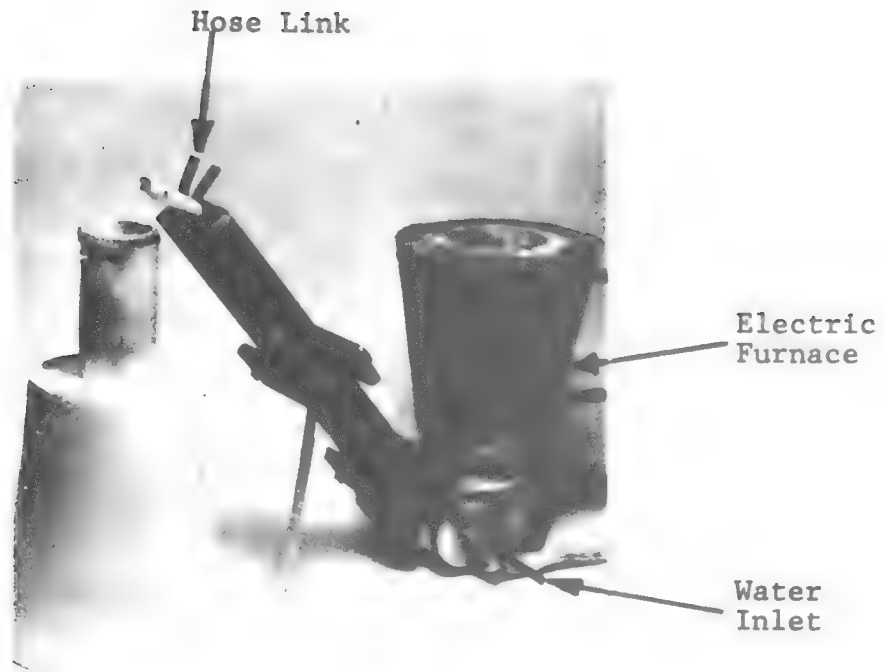
Figure 30. Rail Propulsion Conduit
Adjusted to Pour Up
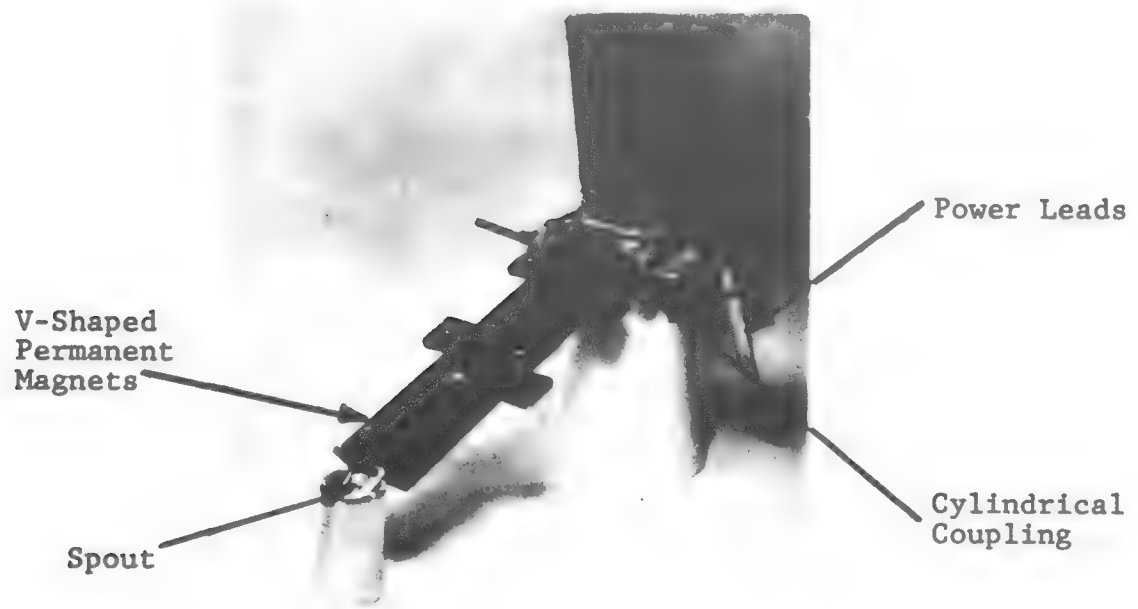
Figure 31. Conduit Used as Valve
for Gravity Pouring.

Figure 32. Conical Induction Coil for Leviation.
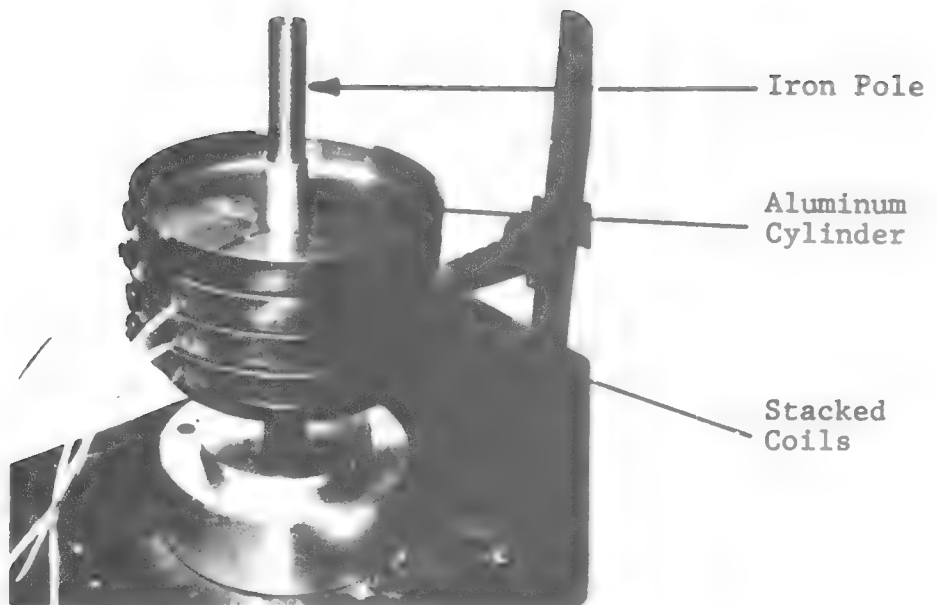
Figure 33. Polyphase Levitation
Pump With Mu-Metal
Flux Concentrators

Figure 34. Three-pole, 3-Phase
Levitation for Lift
and Rotation
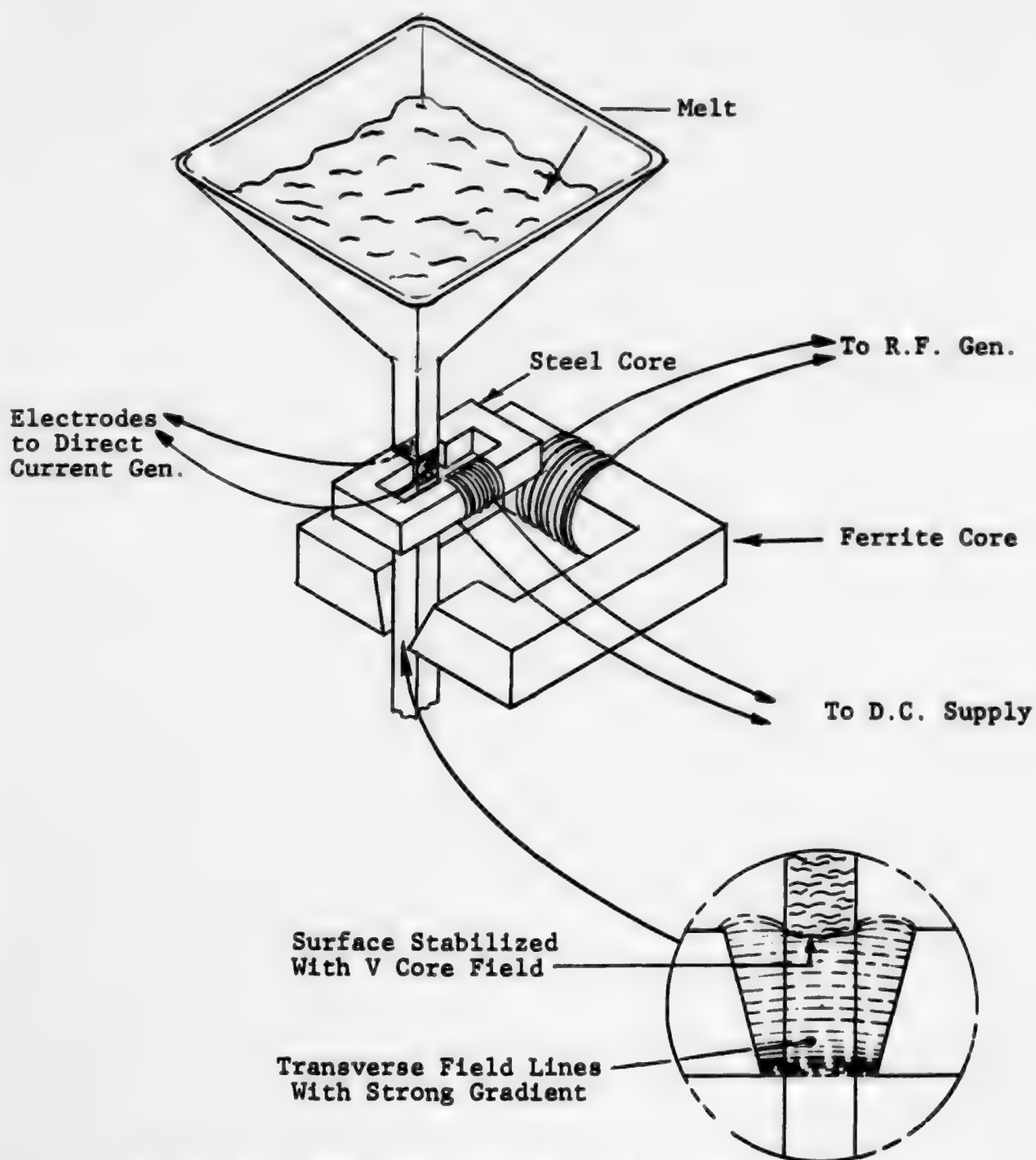
Figure 35.   MHD Conduction Cell With Lower
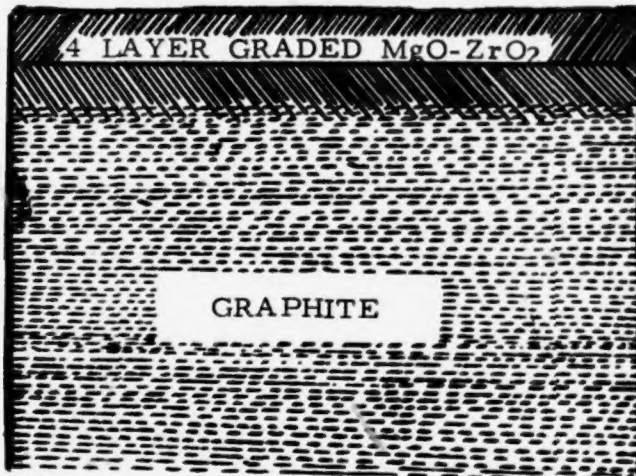Surface Stabilized by A.C. Field
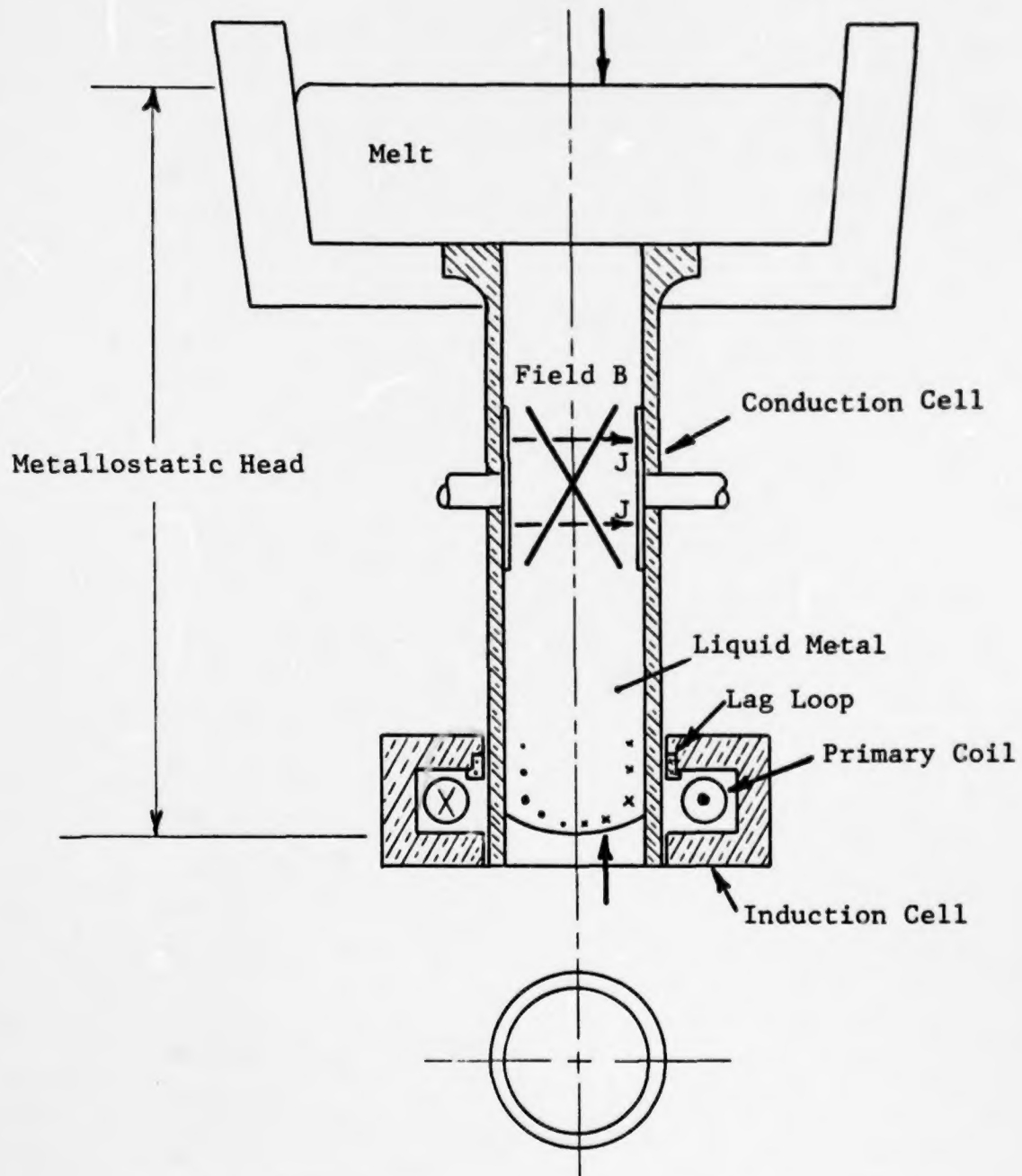
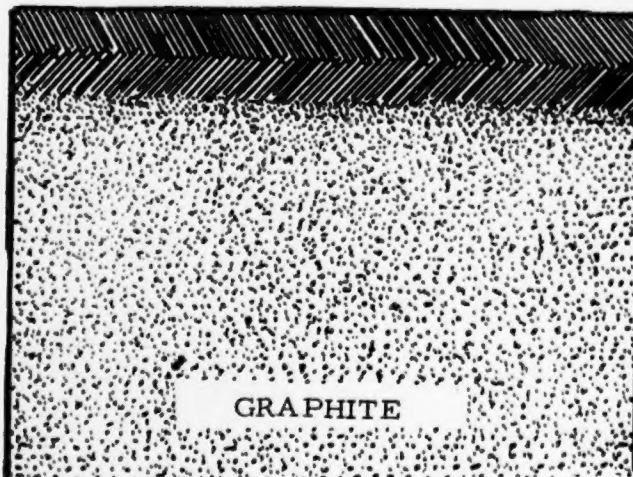Figure 36. MHD Induction Conduction Cell With Lag Loop.
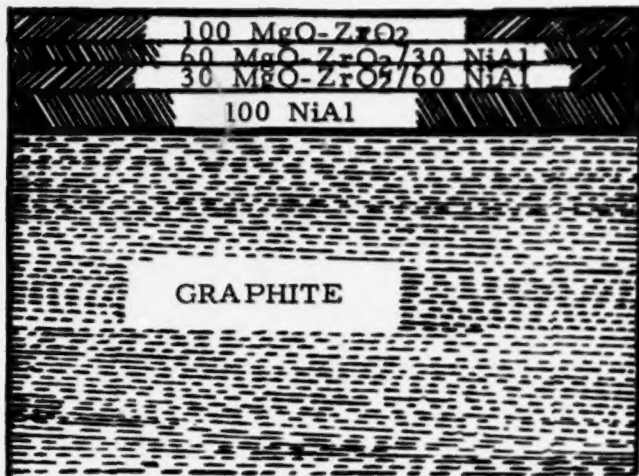
(a) Plasma Sprayed Four Layer Graded MgO-ZrO$_2$ Coating On Graphite Surface.

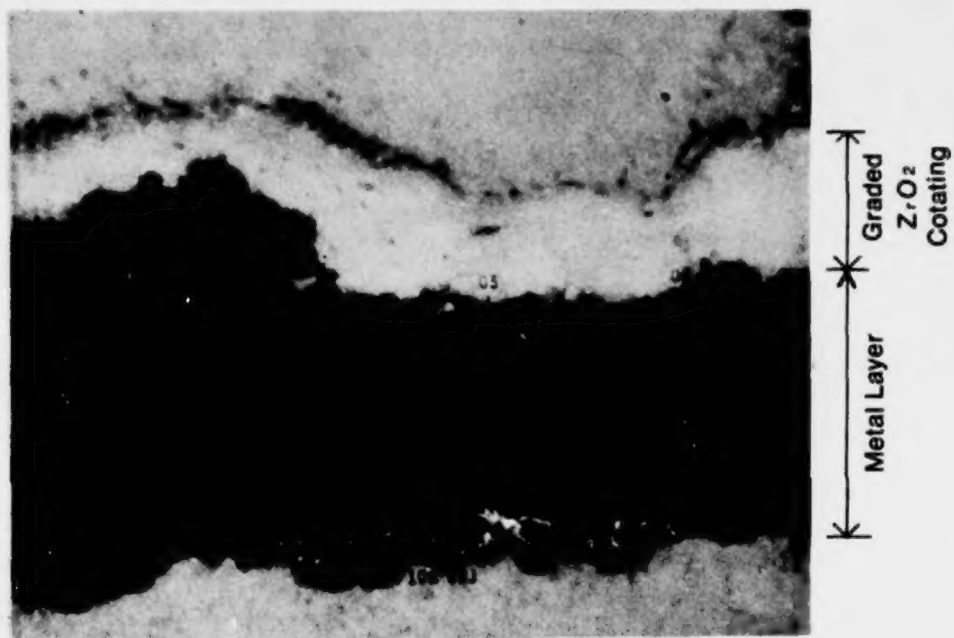(b) Plasma Sprayed Four Layer Graded MgO-ZrO$_2$ Coating on Diffusion Bonded Carbide Layer of Graphite.

(c) Diffusion Bonded Oxide-Carbide Coatings on Graphite.

Figure 37. Multiple Layer Graphite Coatings.

100X
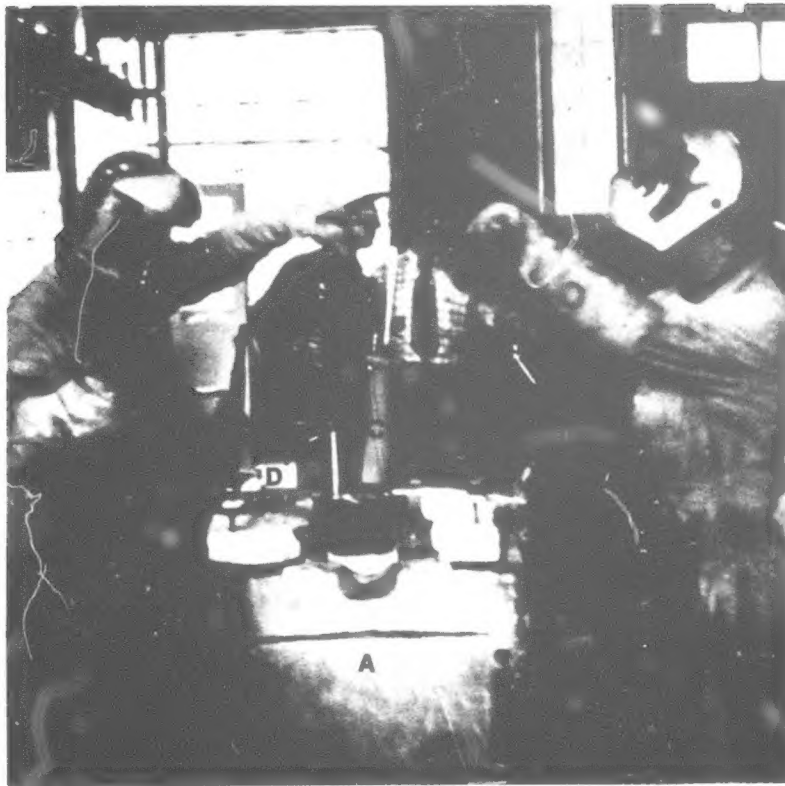
Figure 38. Micrograph (Taken Using Polar-
ized Light) Showing Layer of
Metal Undernearth the Coating.

Figure 39. Dip Test Experiment.